Merging NNLO with Parton Shower

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Questions

- **Why do NNLO ?**
- **Why do Parton Shower?**

Questions

- **Why do NNLO ?**

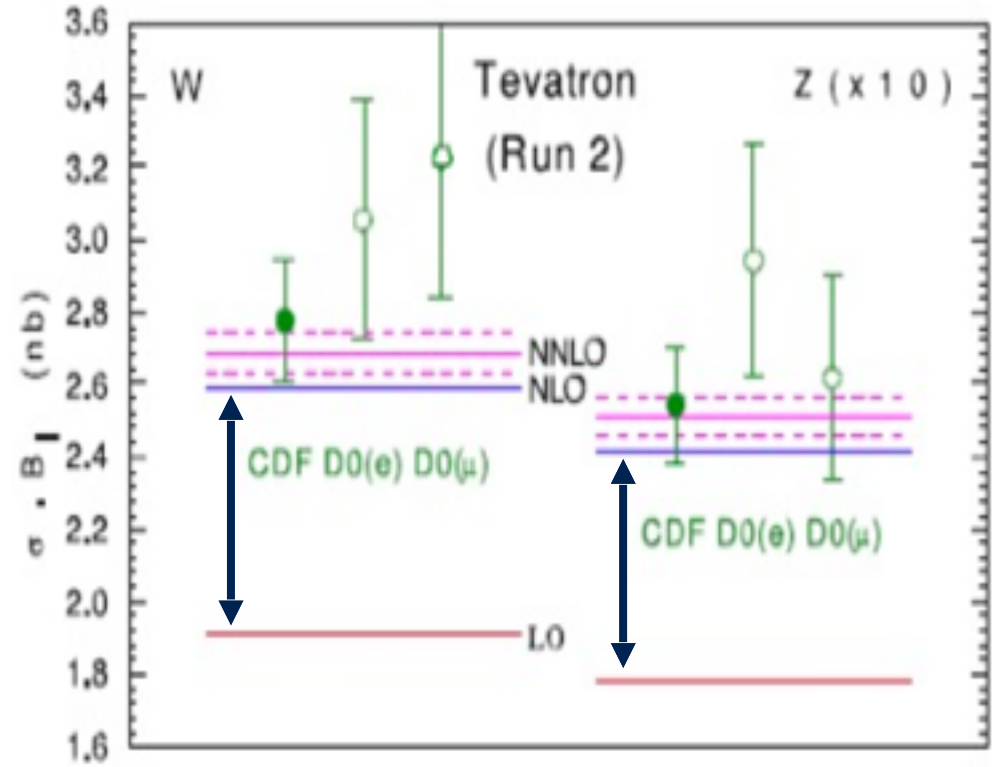
  Quantitative predictive power only starts at NLO; need NNLO for high precision

- **Why do Parton Shower?**

Need Higher Order

Campbell, Ellis, Williams
arXiv:1105.0020

$\sqrt{s}$ [TeV]	$\sigma^{LO}(W^+Z)$ [pb]	$\sigma^{NLO}(W^+Z)$ [pb]
7	6.93(0)	$11.88(1)^{+5.5\%}_{-4.2\%}$
8	8.29(1)	$14.48(1)^{+5.2\%}_{-4.0\%}$
9	9.69(1)	$17.18(1)^{+4.9\%}_{-3.9\%}$
10	11.13(1)	$19.93(1)^{+4.8\%}_{-3.7\%}$
11	12.56(1)	$22.75(2)^{+4.5\%}_{-3.5\%}$
12	14.02(1)	$25.63(2)^{+4.3\%}_{-3.3\%}$
13	15.51(2)	$28.55(2)^{+4.1\%}_{-3.2\%}$
14	16.98(2)	$31.50(3)^{+3.9\%}_{-3.0\%}$



- **Quantitative predictive power only starts at NLO**

Status of NLO

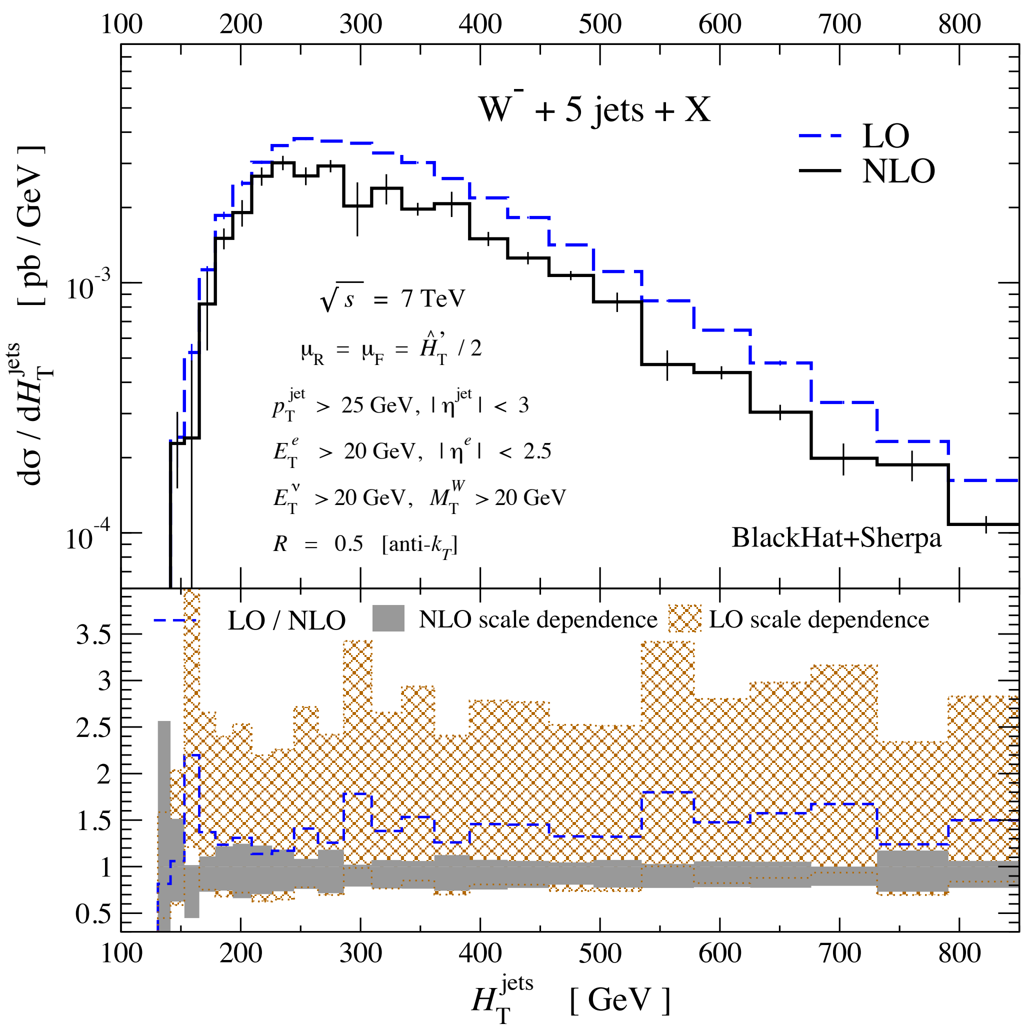
disclaimer:
not a complete list
personally biased

- Rapid progress towards full automation: GoSam, OpenLoop, MadLoop, …
  - Thanks to newly developed techniques such as Unitarity method, OPP etc.

    Bern, Dixon, Dunbar, Kosower; Ossola, Papadopoulos, Pittau; Ellis, Giele, Kunszt, Melnikov, …
  - Tools for tensor integral reduction: GOLEM, Collier, …

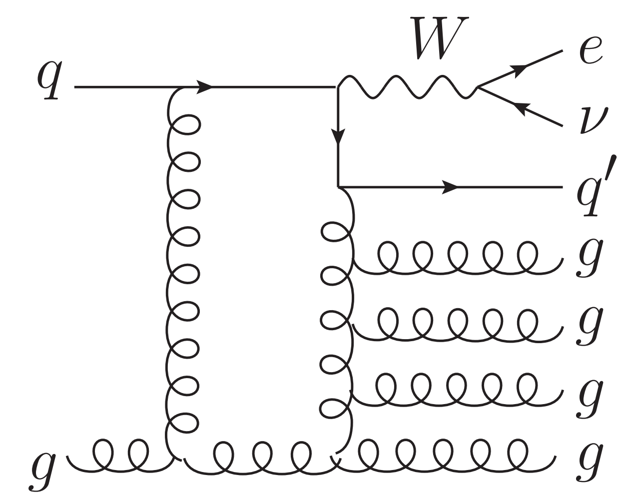
    Denner, Dittmaier; Binoth, Guillet, Pilon, Heinrich, Schuber; …
  - Tools for OPP based reduction: CutTool, Samurai, Ninja …
  - Unitarity method: Blackhat

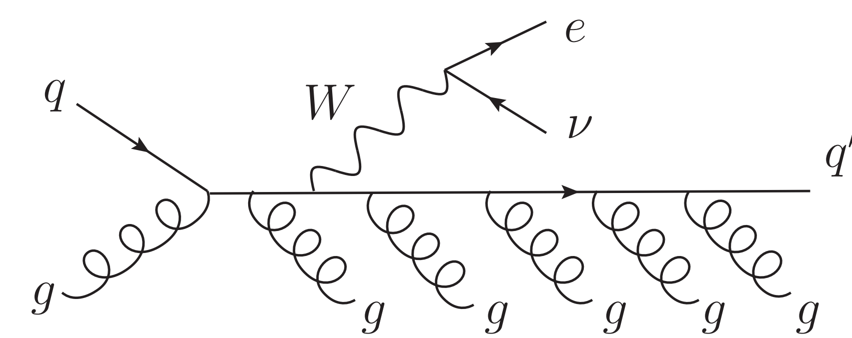
Status of NLO



W + 5 jets NLO by Blackhat+Sherpa (first 2 -> 6 NLO !)

Berger, et al. arXiv:1304.1253



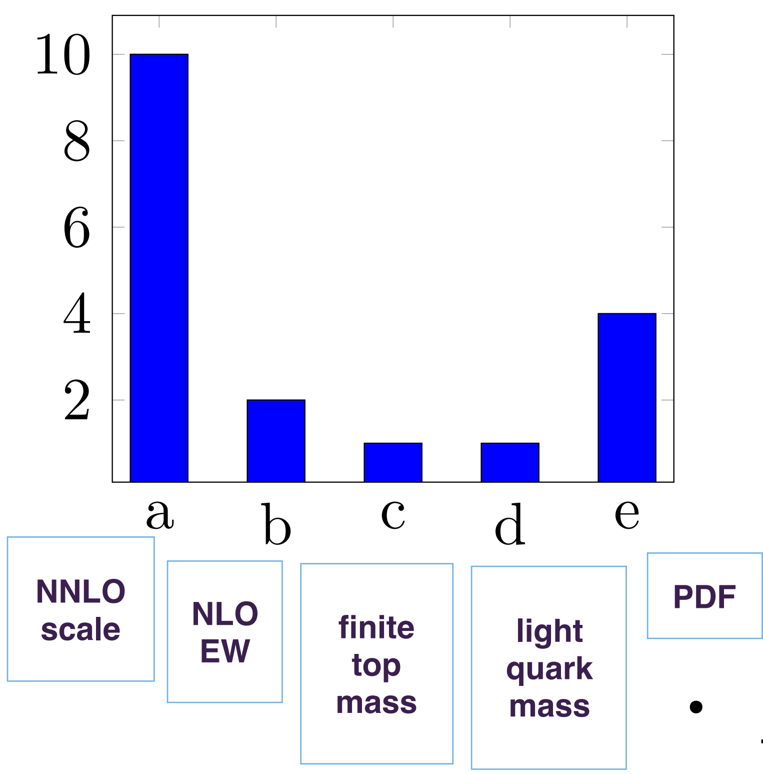


- **Even more impressive when it comes to multi-leg NLO calculation**
  - **Number of diagrams increases factorially with each additional final state particle**

Status of NNLO

- **Study at LHC mandates precision of NNLO and beyond**
  - **Especially needed for Higgs !**
    - **projected experimental uncertainty at percent level, while NLO K-factor ~ 2**

Higgs working group report



CMS snowmass workgroup report

L (fb^{-}1)	$\gamma\gamma$	WW	ZZ	$b\bar{b}$
300	[6%, 12%]	[6%, 11%]	[7%, 11%]	[11%, 14%]
3000	[4%, 8%]	[4%, 7%]	[4%, 7%]	[5%, 7%]

- ***Drell-Yan and Higgs*** **@ NNLO known for a while**

  Harlander, Kilgore; Anastasiou, Melnikov; Ravindran, Smith, van Neerven

  Hamberg, van Neerven, Matsuura

  - **Both color singlet production: simple b/c QCD correction in initial state only**

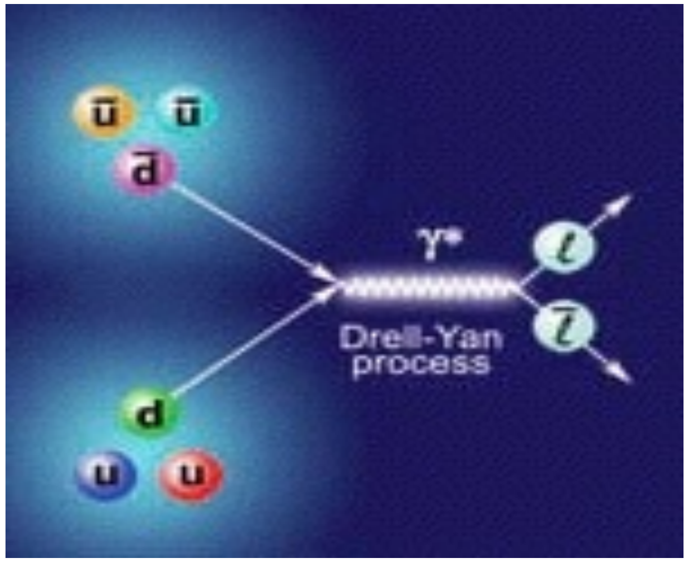
the focus of this talk

Intro: Higgs via Gluon Fusion

- Finally found Higgs … need to know if it is SM-like
  - Best prediction from the SM bears ≈15% theoretical uncertainty even at NNLO
    - N3LO calculation well underway; recently results at threshold becomes available Anastasiou, Duhr, Dulat, Furlan, Gehrmann, Herzog, Mistlberger
      YL, Manteuffel, Schabinger, Zhu
  - Mixed EW QCD correction at NNLO worked out in 2008, suggests a good approximation using factorized approach in combining EW and QCD corrections Actis, Passarino, Sturm, Uccirati
    Anastasiou, Boughezal, Petriello
  - Gluon Higgs effective coupling calculated to 5 loops in infinite top mass limit (2005); full top mass effect known up to NLO, and NNLO top mass dependence estimated (2009) Schroeder, Steinhauser; Chetyrkin, Kuhn, Sturm
    Spira; Anastasiou, Bucherer, Kunszt
- Available fully differential code at NNLO
  - FeHiP/FehiPro, HNNLO Catani, Grazzini, Sargsyan
    Anastasiou, Melnikov, Petriello, Bucherer, Bucherer, Kunszt, Lazopoulos, Stoeckli

Intro: Drell-Yan Process

- Drell Yan process is crucial at hadron colliders
  - Detector Calibration
  - Luminosity Monitor
  - PDF Determination
  - New Physics Search
  - QCD and EW Study
- Very stable expansion in perturbative calculation
- Theoretical error below percent level



- qT resummation worked out using several different analytic methods and experimental data available for comparison
- Fully differential code at NNLO in QCD
  - FEWZ, DYNNLO

Melnikov, Petriello, Gavin, YL, Quackenbush

Catani, Cieri, Ferrera, De Florian, Grazzini,

Prospect of NNLO

- **NNLO now a booming industry:**
  H+1jet, top pair, di-boson, …

  Boughezal, Caola, Melnikov, Petriello, Schulze; Chen, Gehrmann, Glover, Jaquier
  Czakon, Fiedler, Mitov; Abelof, Gehrmann-De Ridder, Maierhoefer, Pozzorini
  Cascioli, Gehrmann, Grazzini, Kallweit, MaierHoefer, von Manteuffel,
  Pozzorini, Rathlev Tancredi, Torre, Weihs, Anastasiou, Duhr, Lazopoulos

  - **Loop calculation**
    - **Many known but multi-scale 2-loop integrals still a big challenge**

      Gehrmann, Jaquier, Glover, Koukoutsakis, Tancredi, Weihs
      Henn, Melnikov, Smirnov
      …

  - **Phase space integration (IR regularization)**

      Catani, Grazzini

    - **qT-subtraction method;**

      Gao, Li, Zhu

      Cut-off method by phase space slicing;
      Phase space partitioning and sector decomposition;

      Czakon, Mitov; Boughezal, Melnikov, Petriello

      Antenna subtraction.

      Abelof, Bernreuther, Bogner, Dekkers, Gehrmann-De Ridder, etc.

Questions

- Why do NNLO ?

Quantitative predictive power only starts at NLO;
need NNLO for high precision, especially for Higgs !

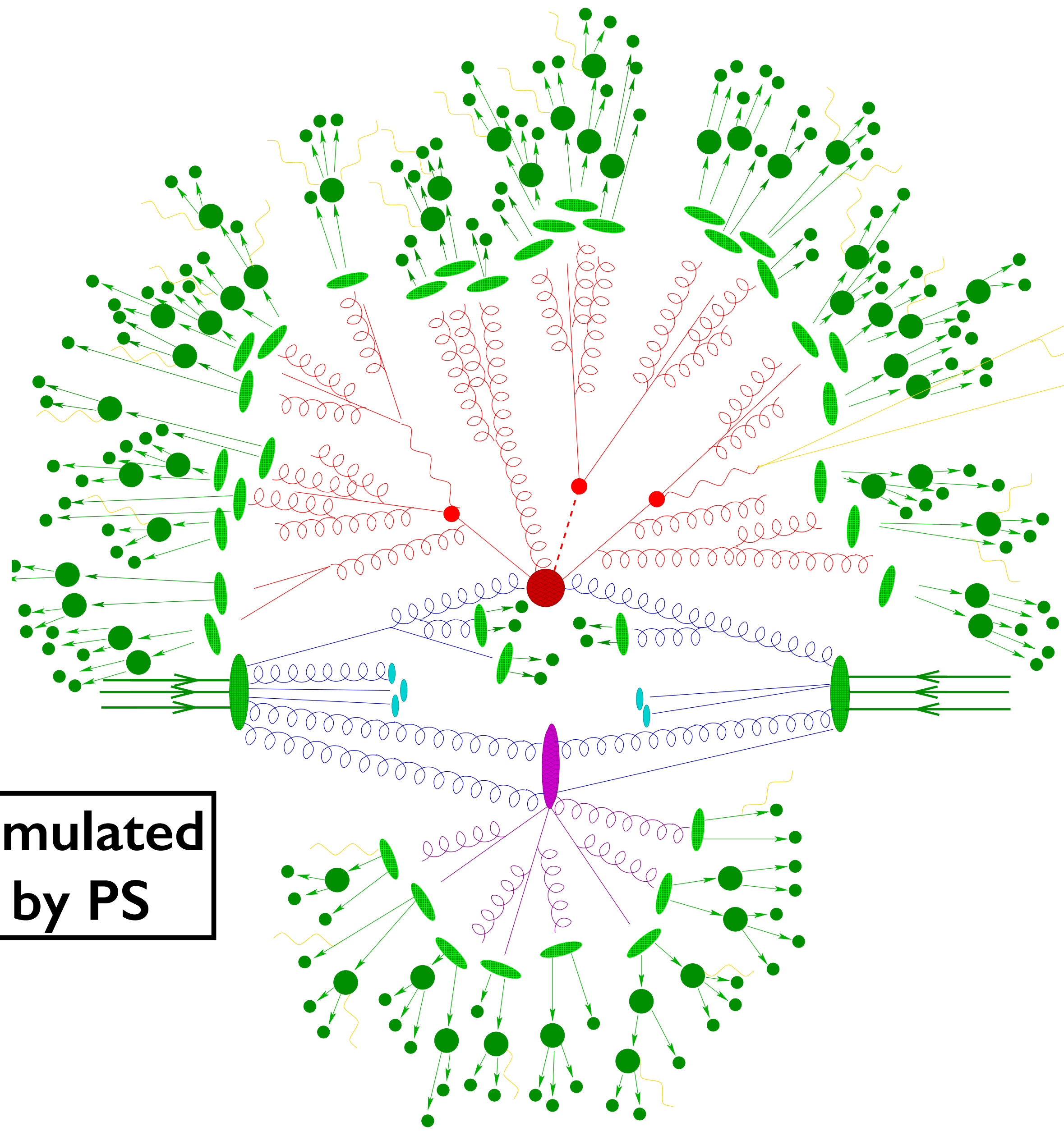
- Why do Parton Shower?

Partonic level events not enough for detector simulation,
need hadronic level events

What is Parton Shower

- **Very complicated environment inside LHC**
- **Short distance physics obscured by long distance ones**
    - **Initial state radiation**
    - **Final state radiation**
    - **Hadronization**
    - **Multiple Parton Interaction**
    - **...**

Simulated by PS



PS bridges theoretical calculation with detector simulation

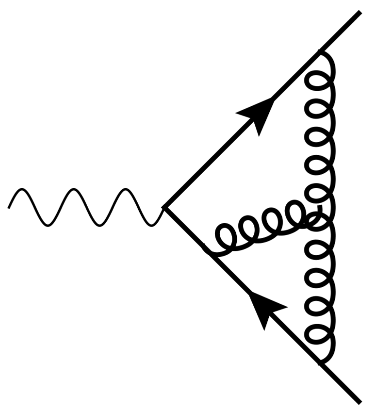
Enough?

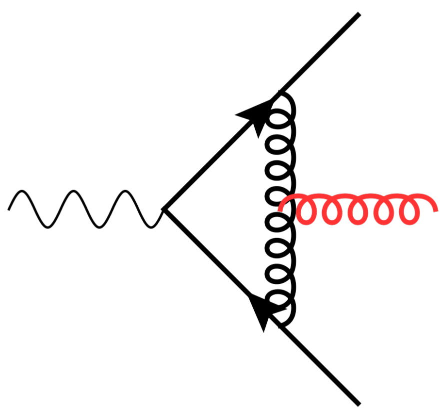
PS bridges theoretical calculation with detector simulation

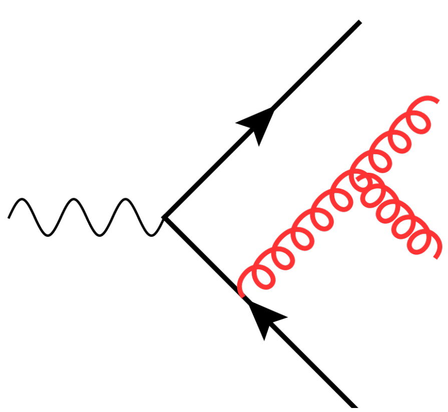
LO or NLO at best

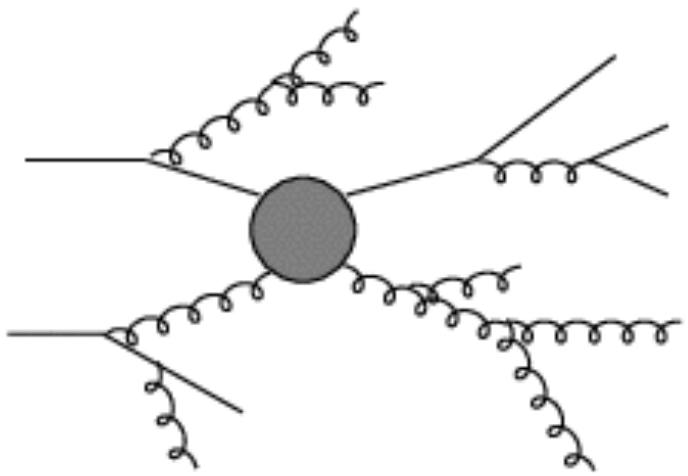
- Current way of interfacing NNLO is rather crude
  - Differential NNLO K-factor
- Intrinsic difficulty in combining NNLO with PS
  - Problem starts at NLO

(N)NLO and Parton Shower









- Two Parts of (N)NLO:
  - Loops / Virtual:
    - <u>IR divergent</u> by itself ⇒ cannot shower divergence
  - Emissions: up to 1 or 2 for (N)NLO
    - PS have 0 to ∞ emissions ⇒ <u>double counting</u>

(N)NLO and Parton Shower

- Problem 1: <u>IR divergence</u>
  - Fixed order has delicate cancellation between real and virtual
  - Parton shower eliminates divergence by resummation
- Problem 2: <u>double counting</u>
  - Fixed order adopts true ME
  - Parton shower ME is only approximate

IR singularity

- Real Emission ME is singular in IR limit
    - KLN theorem guarantees that IR sing. cancel between Real and Virtual

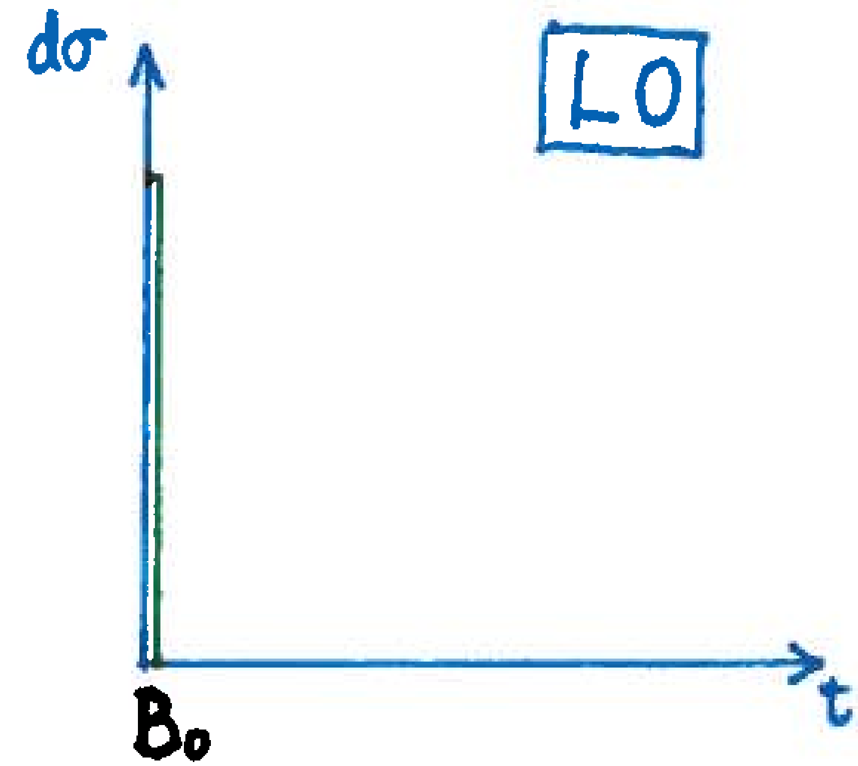
cancel !

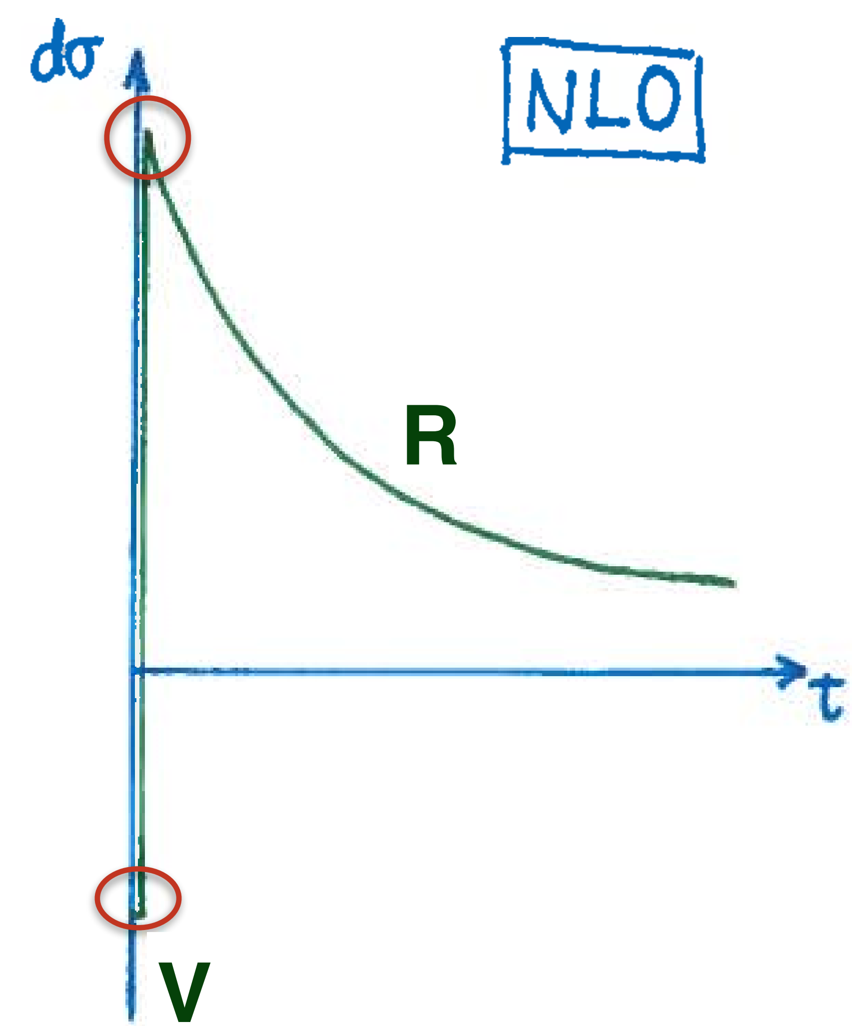
$$V \propto \frac{1}{\epsilon}\delta(t)$$

$$R \propto t^{-1-\epsilon} = -\frac{1}{\epsilon}\delta(t) + [t^{-1-\epsilon}]_+$$

plus distribution prescribes a sharp subtraction at t=0 to ensure finite inclusive result

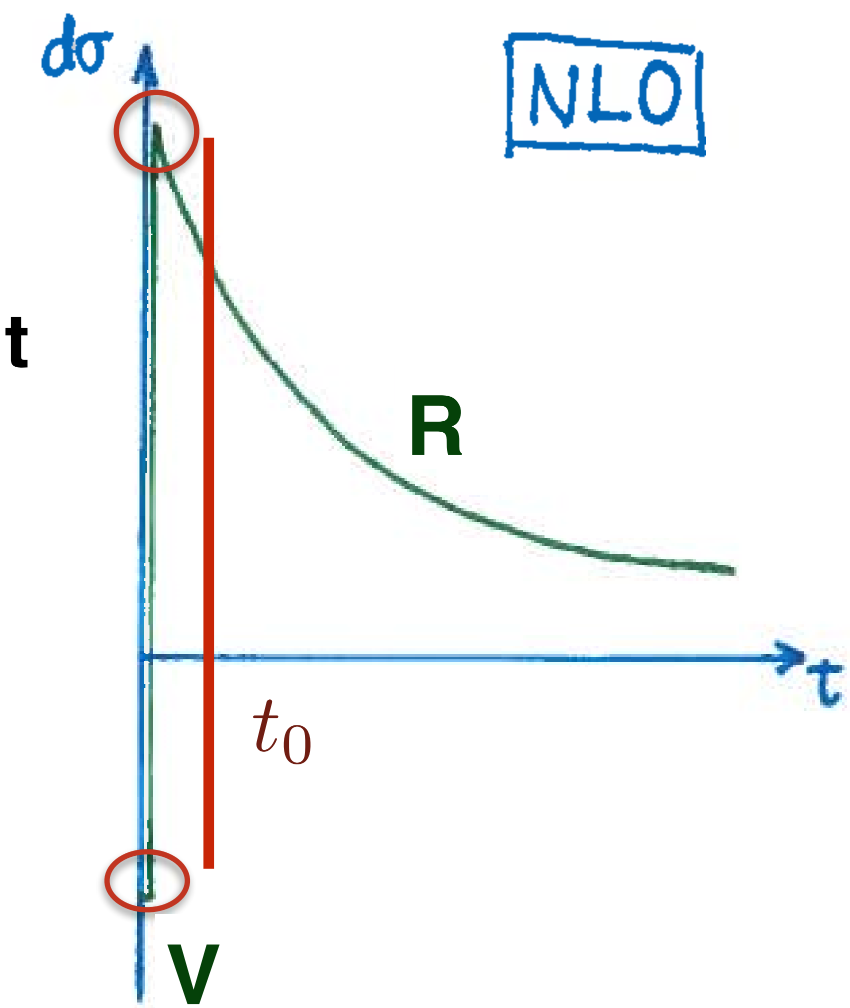
$$\int dt\,[f(t)]_+ g(t) = \int dt\,[f(t)]_+ \{g(t) - g(0)\}$$





IR singularity

- **IR-finite only inclusively: R diverges as it approaches t=0**
- **A simple way to do differential NLO is to have a cut-off that's below observable limit**
    - **below cut-off: Combined with Virtual**
    - **above cut-off: IR-div. regulated by cut-off**



$$R \propto t^{-1-\epsilon} = -\frac{1}{\epsilon} + [t^{-1-\epsilon}]_+$$

$$\xrightarrow{t_0 \to 0} -\frac{1}{\epsilon} + \log(t_0)\delta(t) + \frac{1}{t}\theta(t - t_0) + \mathcal{O}(\epsilon)$$

logarithmic dependence on cut-off

Logarithms

- **Observables like pT effectively introduce a cut-off**

$$\Rightarrow \; L = \log(t_0)$$

  - **NLO: up to 1 emission**
    - **next-to-leading-logarithm (NLL)**

$$\alpha_S(L^2, L)$$

  - **NNLO: up to 2 emissions**
    - **next-to-next-to-leading-logarithm (NNLL)**

$$\alpha_S(L^2, L) + \alpha_S^2(L^4, L^3, L^2, L)$$

- **FO becomes unstable when *L* becomes large ⇒ resummation**

IR Singularity in Parton Shower

- **Parton shower takes a different approach**

$$\lim_{t\to 0} e^{-1/t}\frac{1}{t} \to 0$$

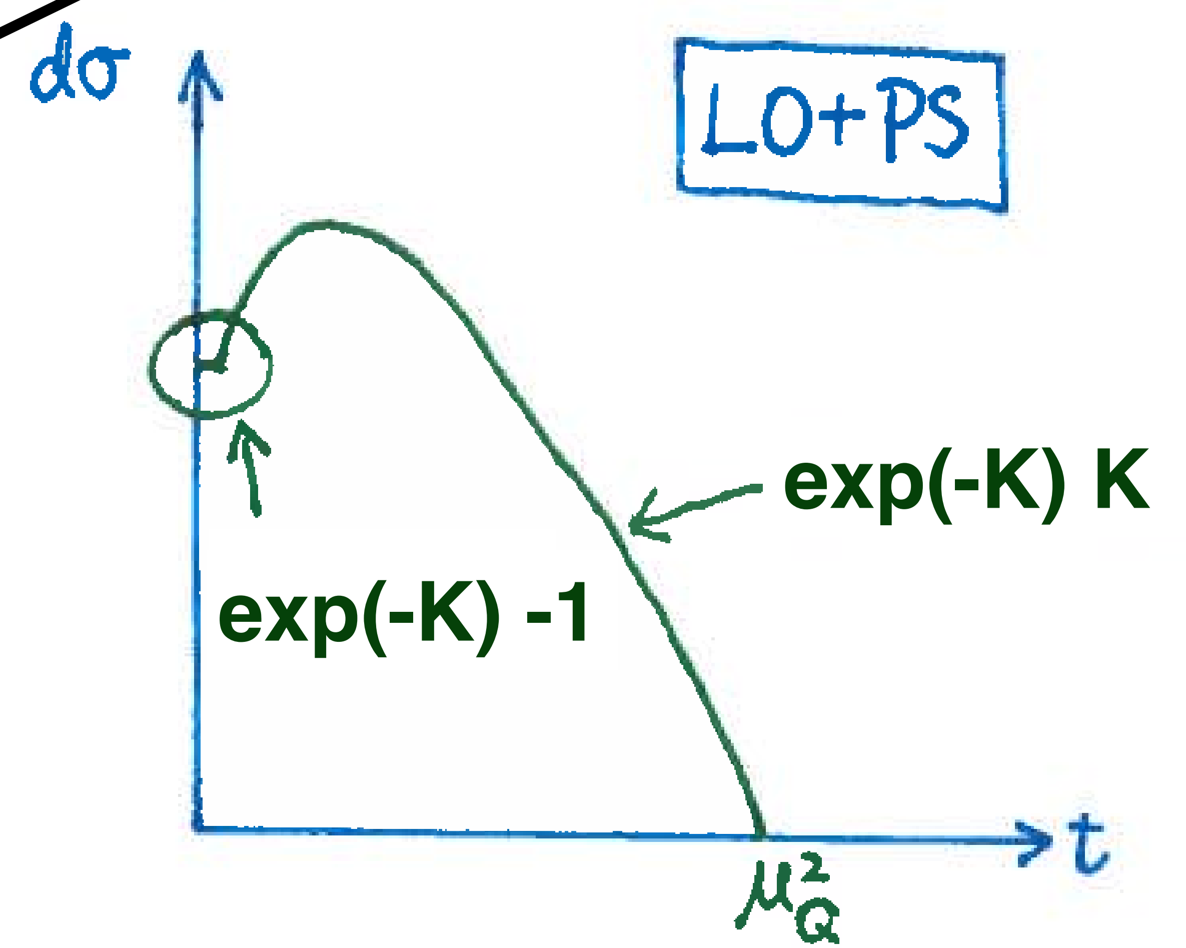
  - **Singularity suppressed by Sudakov**

V=-R=-K if neglecting IR-finite terms

$$V \to e^V - 1 \xrightarrow{} e^{-K} - 1$$

$$R \to e^{-K} K$$

$\boxed{\text{Sudakov Form Factor}}$

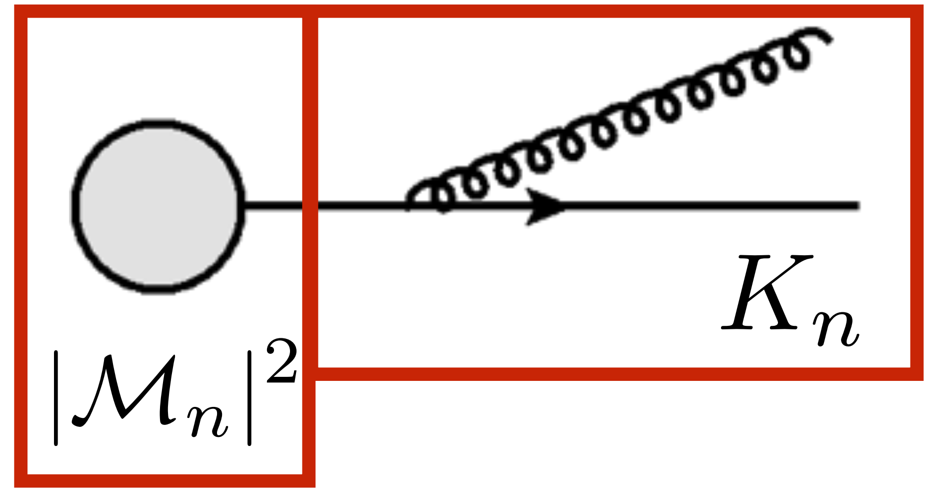


K is approximately *R* ; approaching *R* in IR limit

Parton Shower Basics

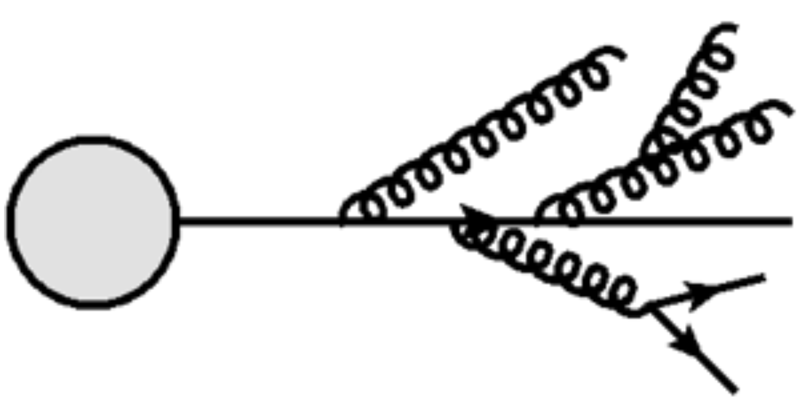
- **In the IR limit, the ME takes a factorized form**

$$|\mathcal{M}_{n+1}|^2 \sim K_n |\mathcal{M}_n|^2$$



- **Multiple emissions are approximated by iterating the above formula**

hard scale to start PS



$$1 + \int_{t_c}^{\mu_Q^2} dt\, K_n + \int_{t_c}^{\mu_Q^2} dt\, K_n \int_{t_c}^{t} dt\, K_{n+1} +$$

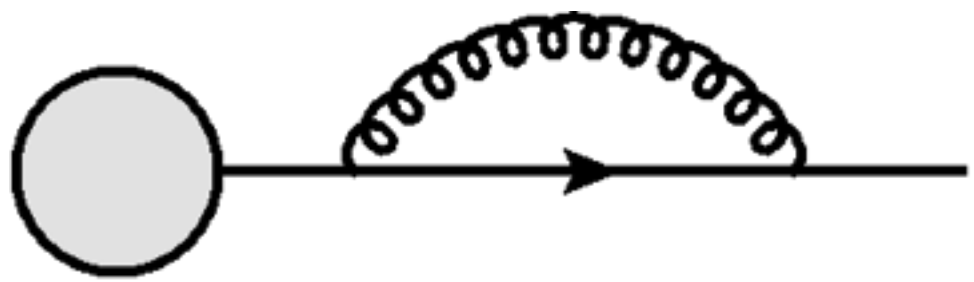
$$\int_{t_c}^{\mu_Q^2} dt\, K_n \int_{t_c}^{t} dt'\, K_{n+1} \int_{t_c}^{t'} dt''\, K_{n+2} + \ldots$$

terminating scale to regularte IR div.

t_c is always set below the observable limit

Parton Shower Basics

- **Approximate Virtual by integrated Real**



$$|\mathcal{M}_n^{1-\text{loop}}|^2 \sim \left(- \int_{t_c} dt\, K_n \right) |\mathcal{M}_n|^2$$

- **A "failed" attempt to emit**
- **Iterated Virtual gives Sudakov form factor**

e^{-K}

$$\Pi_n(t_c, \mu_Q^2) = \exp\left\{ - \int_{t_c}^{\mu_Q^2} dt\, K_n \right\} = 1 - \int_{t_c}^{\mu_Q^2} dt\, K_n(t) \Pi_n(t, \mu_Q^2)$$

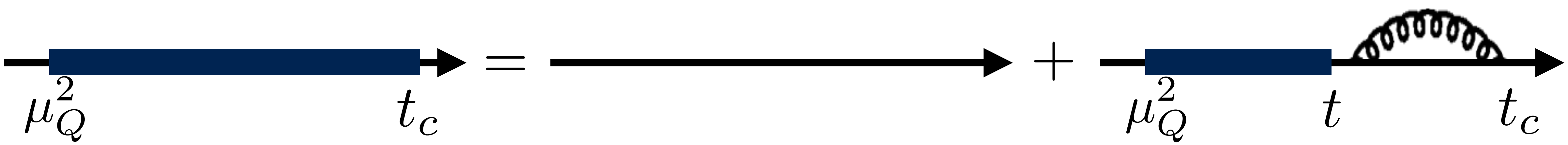
Parton Shower Basics

failed emission @ t

$$\Pi_n(t_c,\mu_Q^2) = \exp\left\{-\int_{t_c}^{\mu_Q^2} dt\, K_n\right\} = 1 - \int_{t_c}^{\mu_Q^2} dt\, \underline{K_n(t)}\,\underline{\Pi_n(t,\mu_Q^2)}$$

no emission probability

no emission before t



- **Sudakov calculates zero emission probability in PS evolution**

Rewrite: $\quad 1 = \Pi_n(t_c,\mu_Q^2) + \int_{t_c}^{\mu_Q^2} dt\, K_n(t)\Pi_n(t,\mu_Q^2)$

Parton Shower Basics

Reinterpret:

no emission at all　　　　　1 emission @ t

$$1 = \Pi_n(t_c, \mu_Q^2) + \int_{t_c}^{\mu_Q^2} dt\, \underline{K_n}(t)\underline{\Pi_n(t, \mu_Q^2)}$$

no emission till t

Simplified Form

$$1 = e^{-K} + e^{-K} K$$

Virtual　　Real

- **PS respects unitarity**
  Virtual cancels Real perfectly ⇒ inclusive rate unchanged !

⇩

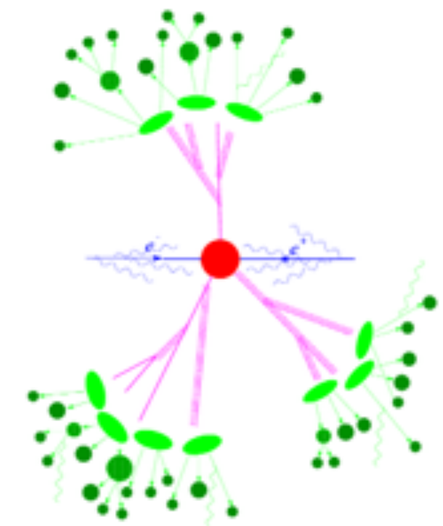
PS Generating Function

PS continues

$$\mathcal{F}_n = \Pi_n(t_c, \mu_Q^2) + \int_{t_c}^{\mu_Q^2} dt\, K_n(t)\Pi_n(t, \mu_Q^2)\underline{\mathcal{F}_{n+1}}$$

recursive def.

Parton Shower



$$\mathcal{F}_n = \Pi_n(t_c, \mu_Q^2) + \int_{t_c}^{\mu_Q^2} dt\, K_n(t) \Pi_n(t, \mu_Q^2) \mathcal{F}_{n+1}$$

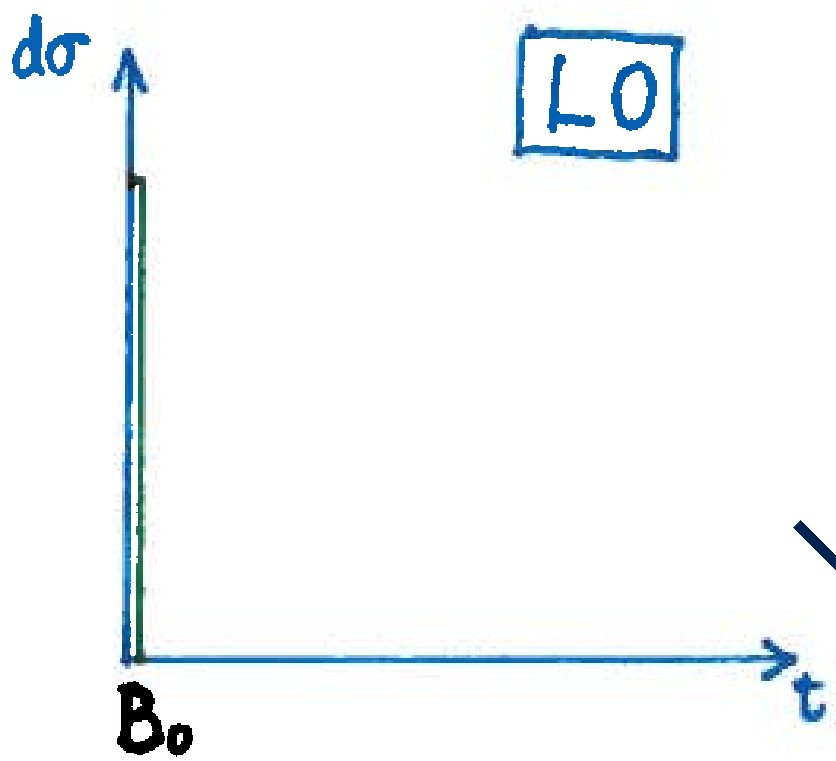
Iterated for more emissions

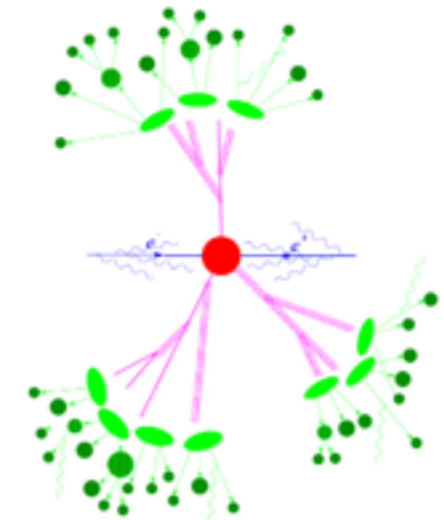
$$1 = e^{-K} + e^{-K} K e^{-K} + e^{-K} K e^{-K} K + \ldots$$

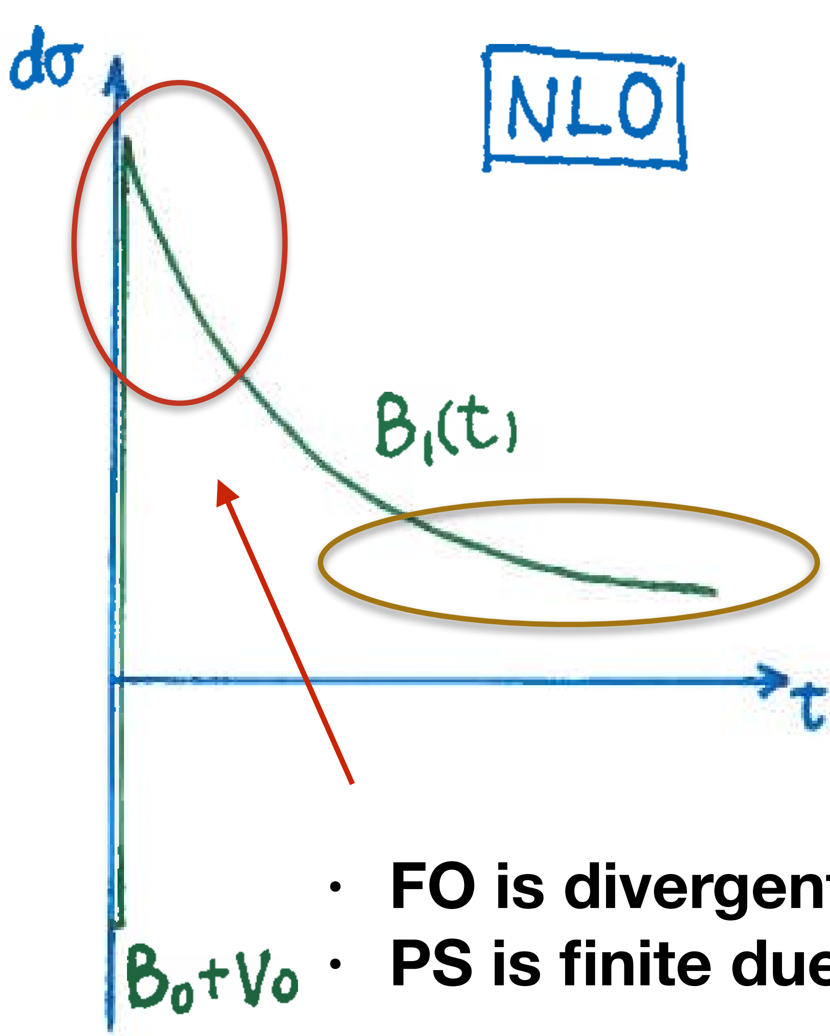
- **Infinite emissions: automatic resummation**
  iterated (ordered) single emissions ⇒ approx. NLL accurate

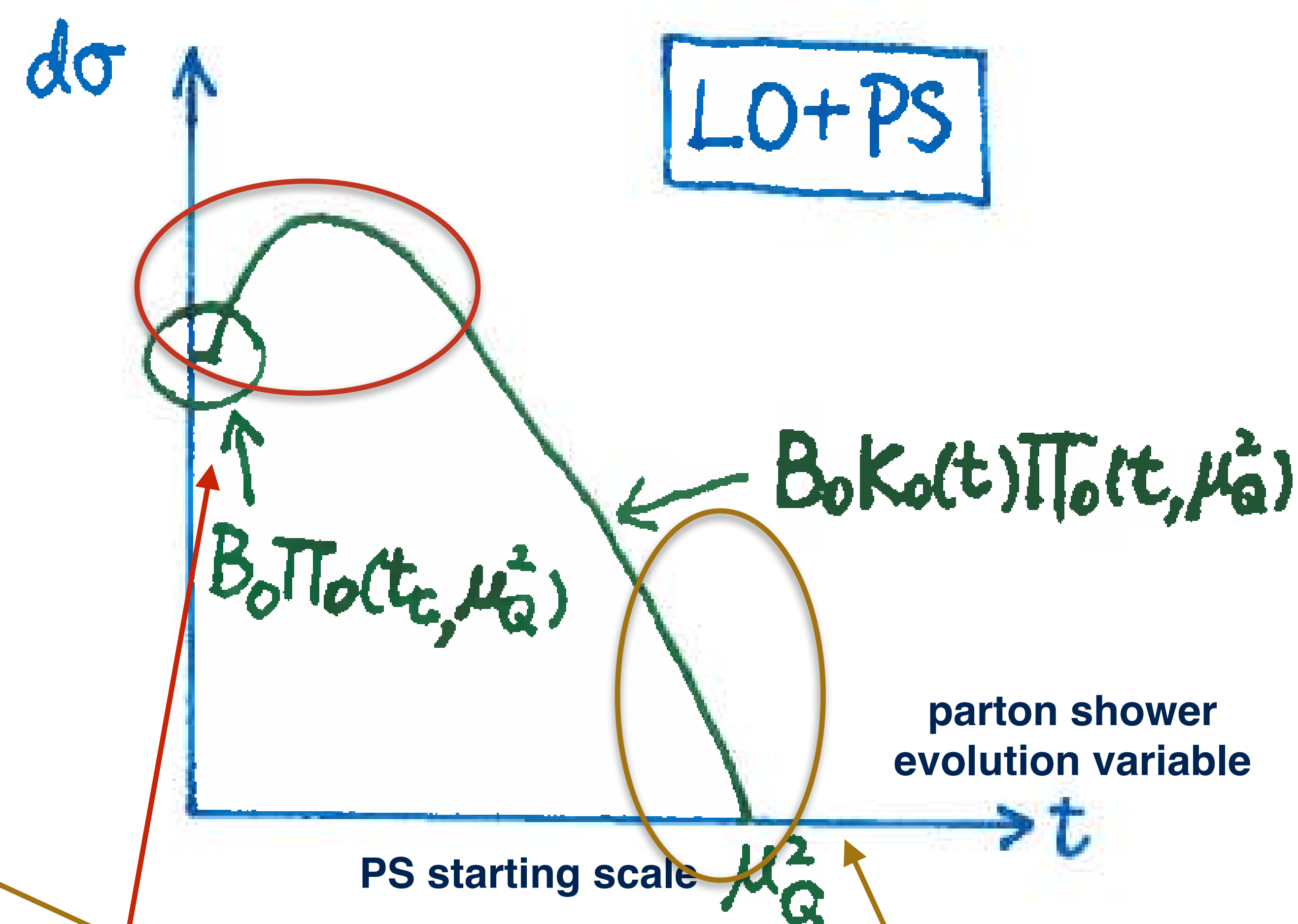
$$\exp\{\alpha_S(L^2, L)\}$$

FO vs PS





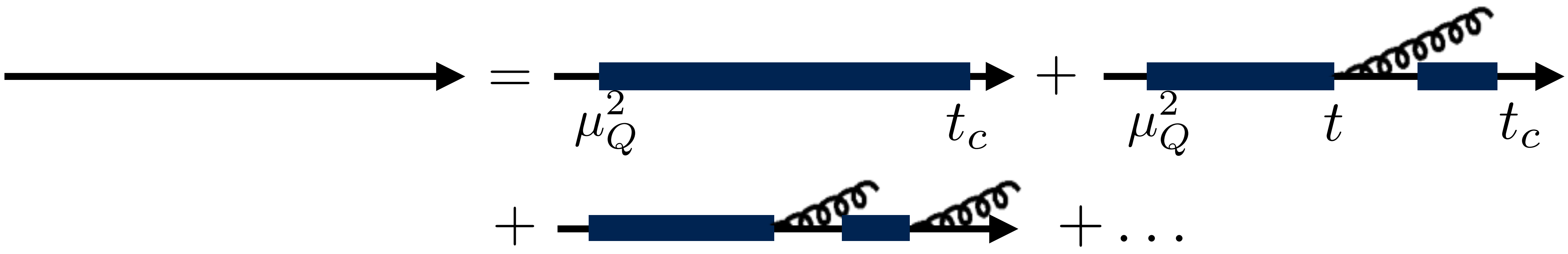




- **FO is divergent in IR region**
- **PS is finite due to Sudakov**

FO should be used in hard region, where PS is no longer reliable

Fix ?



$$1 = e^{-K} + e^{-K}Ke^{-K} + e^{-K}Ke^{-K}K + \ldots$$

- **Each emission can be corrected by actual MEs**

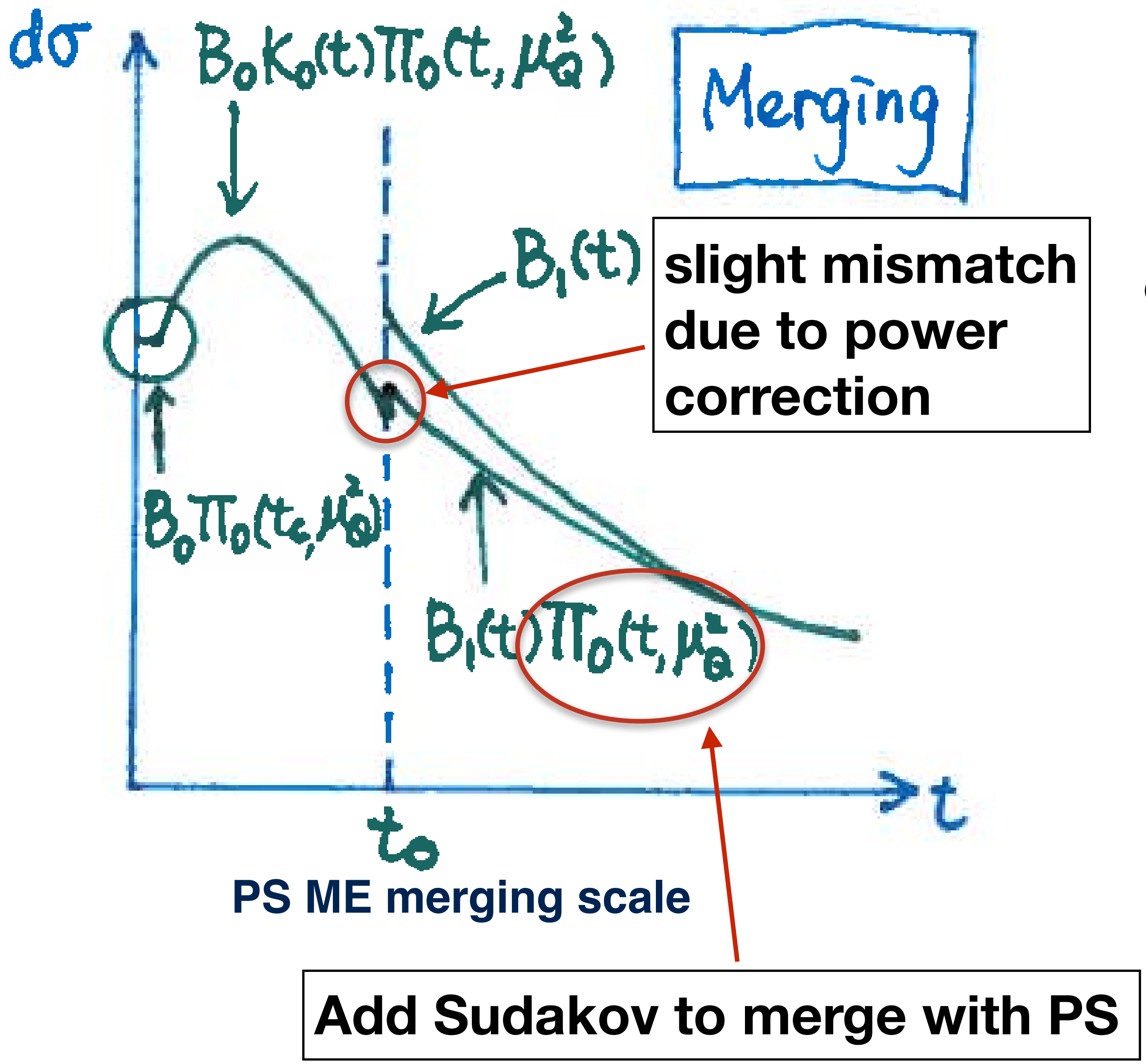
merging scale

$$e^{-K}K \to e^{-K}\left(K|_{t<t_0} + R|_{t>t_0}\right)$$

- **Add ME correction in hard region**
- **Keep PS in IR region**
- **Use <u>merging scales</u> to separate two regions**

"Fix the PS"

$$e^{-K} + e^{-K}K \to e^{-K} + e^{-K}(K|_{t<t_0} + R|_{t>t_0})$$



- **Hard region restored at the expense of unitarity (extra Sudakov fades away)**

$$e^{-K}R = \exp\{-\int_t^{\mu^2} dt' K(t')\}R(t)$$

$$\xrightarrow{t\to\mu^2} R$$

- **Merging scale dependence**
  - **mismatch is IR-finite and vanishes when merging scale becomes small**

$$R - K \xrightarrow{t\to 0} 0$$

Merging

$$e^{-K} + e^{-K}K \to e^{-K} + e^{-K}(K|_{t<t_0} + R|_{t>t_0})$$

- **Merging of MEs:**
  ME correction for each jet multiplicity in PS

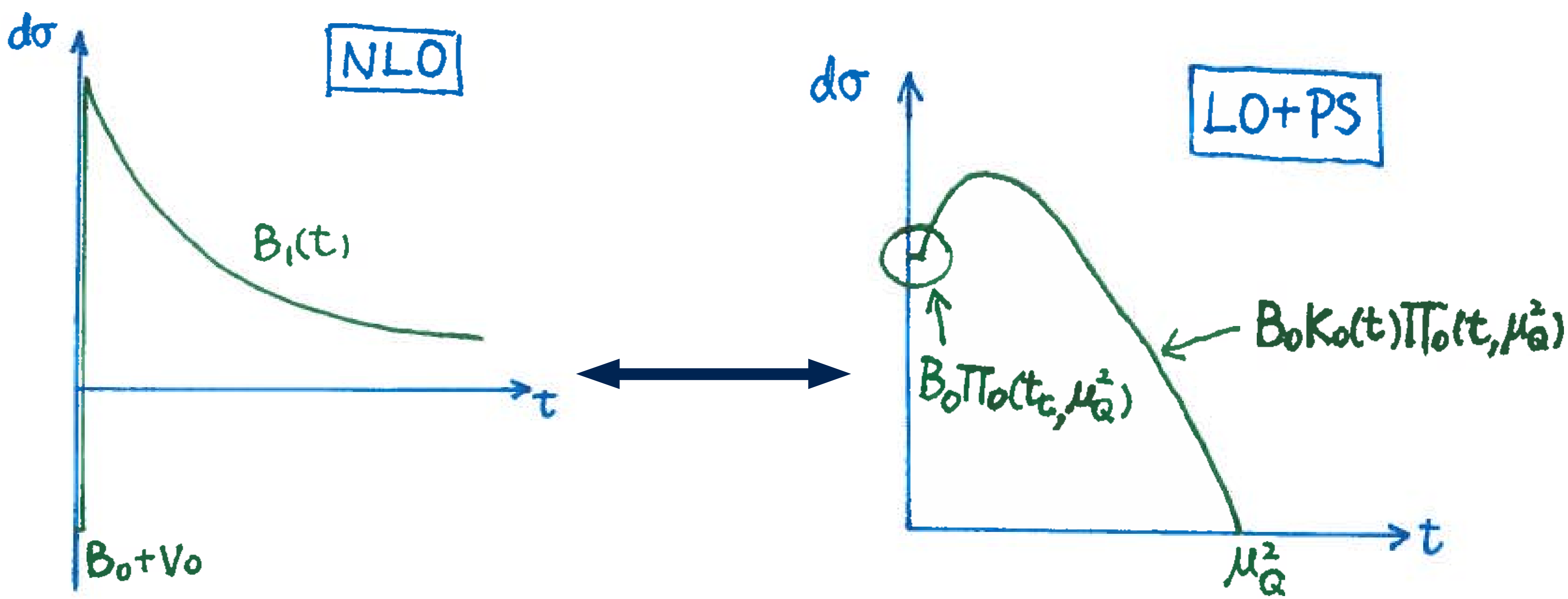
  - **merging scale dependence dominated by subleading logarithmic terms**
    IR limit of many emission ME not fully captured by PS

- **Examples:**
  MLM, CKKW, CKKW-L, Truncated Shower, Pseudo-shower

Catani, Hoeche, Krauss, Kuhn, Lonnblad, Mangano, Mrenna, Richardson, Schumann, Siegert, Webber, …

Matching

- **Would also like to have higher order inclusive accuracy**
  - **correct emission pattern in hard region** × (merging)
  - **keep PS resummation in IR region** × (merging)
  - **correct FO inclusive rate**



Matching @ NLO

- **Apply NLO differential K-factor ?**
  - **PS starts with a single topology**
    All shower emissions have a parent Born topology
  - **LO has only Born topology**
    for H/W/Z production, the final state is exclusively H/W/Z
  - **NLO contains emission ME**
    for H/W/Z production, there is final state of H/W/Z + 1 jet

Combining two multiplicities is addressed by merging
but didn’t do it “right”

Matching @ NLO

For simplicity
take Born B=1

$$\mathrm{NLO}: 1+V+R = (1+V+K) + (R-K)$$

finite

$$\mathrm{PS}: e^{-K} + e^{-K}K$$

finite

$$\mathrm{NLO}\otimes\mathrm{PS}: (1+V+K)(e^{-K}+e^{-K}K) + (R-K)$$

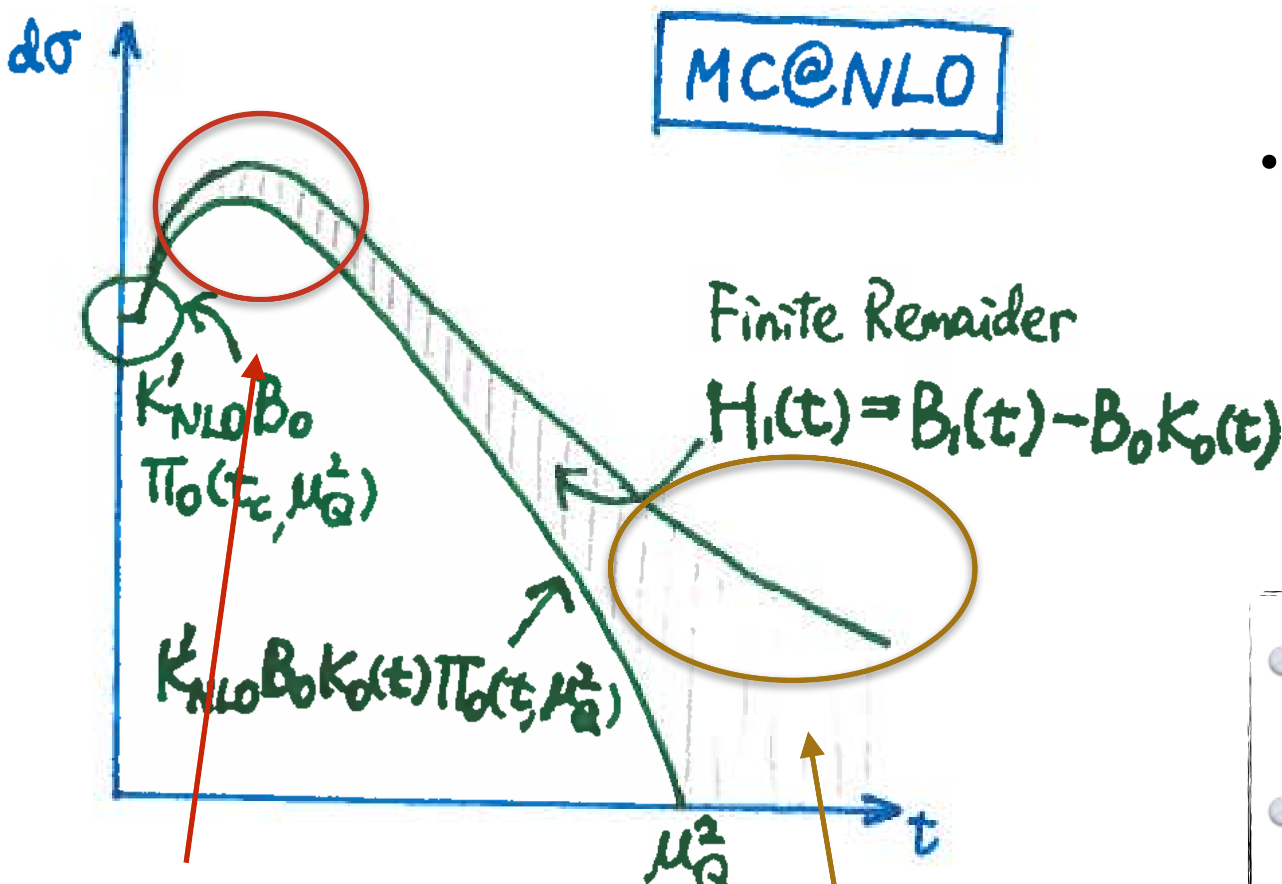
- **Use PS "*K*" as a subtraction term**
  - **Integrated to cancel IR div. in Virtual**
    can be mapped to Born ⇒ <u>(approx.) NLO K-factor</u>
  - **Keep differential to cancel IR div. in Real**
    R-*K* difference is non-singular ⇒ <u>hard remainder</u>
    - **PS makes up the "*K*" part: no double counting**

Matching @ NLO

$k'_{\rm NLO}$

$$(1+V+K)(e^{-K}+e^{-K}K)+(R-K)$$

$=1$ $\qquad H$



$R \to K$
dominated by PS
$k'_{\rm NLO}e^{-K}K+(R-K)$
$\to k'_{\rm NLO}e^{-K}K$

$e^{-K}\to 1$
full ME restored
$k'_{\rm NLO}e^{-K}K+(R-K)\to R+\mathcal{O}(\alpha_S)$

- **Widely used approaches: MC@NLO, POWHEG**

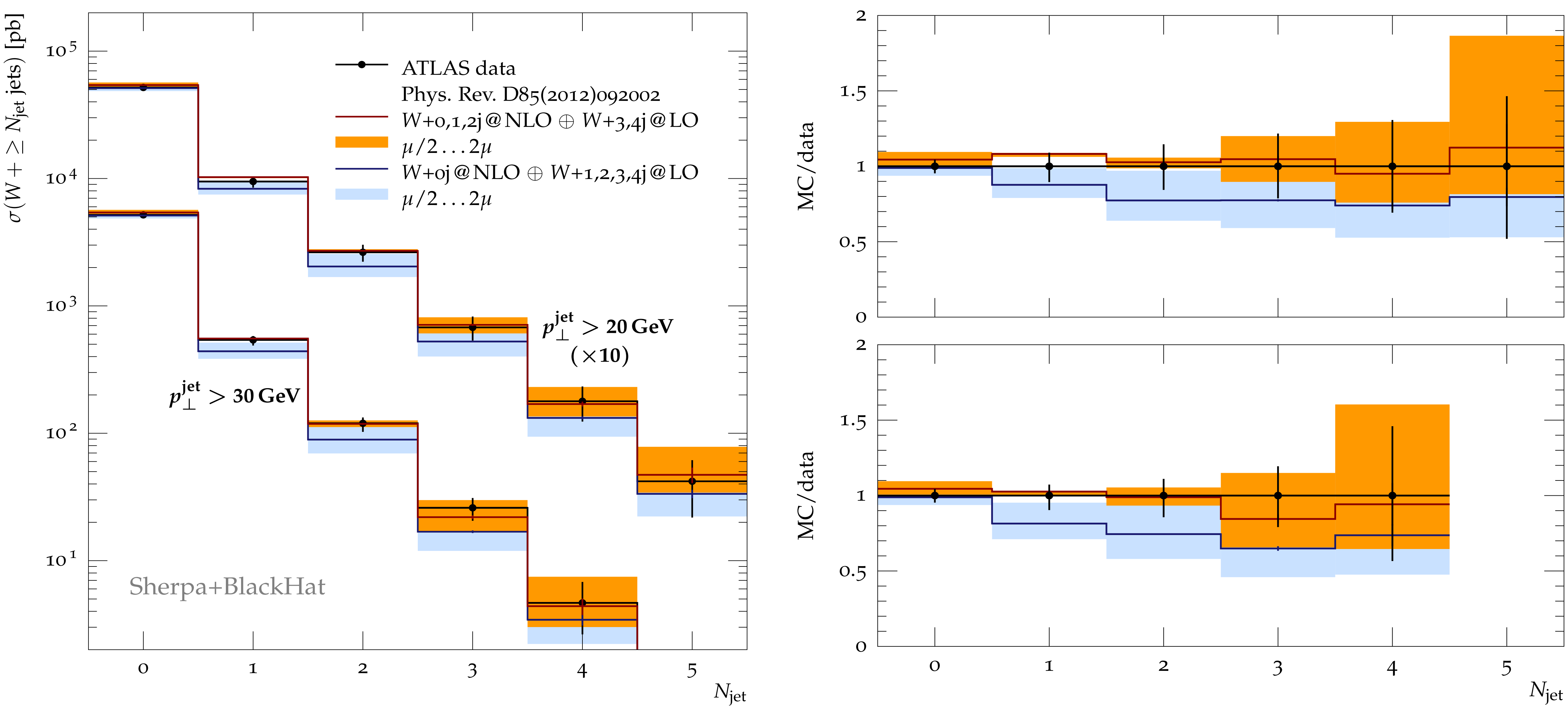
Frixione, Webber, Nason, Oleari

- **POWHEG takes *K=R***

- Correct emission pattern in hard region ×
- Keep PS resummation in IR region ×
- Correct NLO inclusive rate ×

Merged Matching

- **PS matched NLO can also be merged: MEPS@NLO, ...**
  Gehrmann, Hoeche, Krauss, Schoenherr, Siegert ...
  - **Example: W + n jets merged in Sherpa**



Hoeche, Krauss, Schoenherr, Siegert arXiv:1207.5030

Extension to NNLO ?

$$(1+V+K)(e^{-K}+e^{-K}K)+(R-K)$$

- **Require flexible subtraction method of NNLO**
  flexible enough to be used in the PS "K" for numerical Sudakov

Hamilton, Nason, Zanderighi, Re

- **MINLOS overcome the difficulty by using analytic Sudakov**
    - **process-specific**
    - **possible mismatch with Sudakov in subsequent PS**
    - **requires extra input of differential NNLO K-factor**

- **Is there another way to combine FO with PS?**
  can we improve the merging procedure to achieve higher order accuracy?

Unitarized Merging

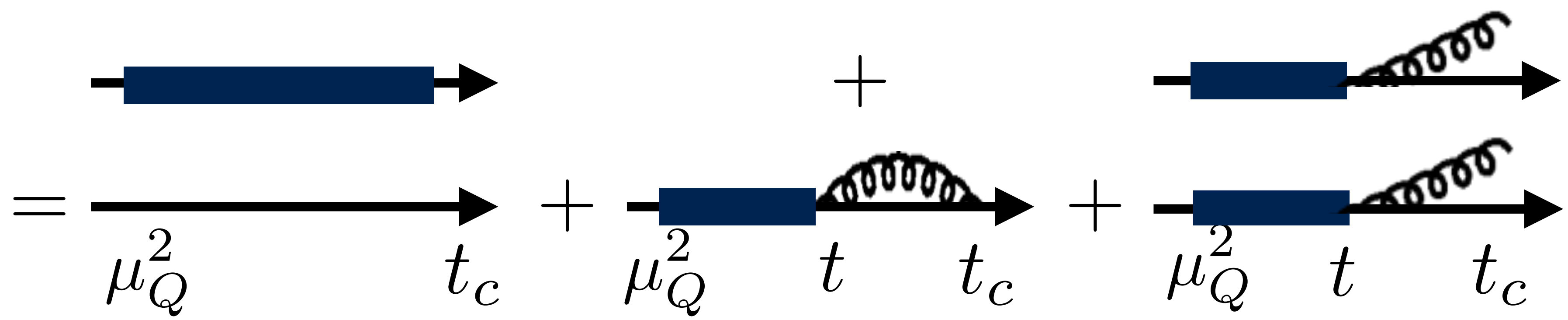
- **First restore unitarity for merging**
  modified Real ⇒ no more perfect cancellation btw Real and Virtual

Lonnblad, Prestel

$$e^{-K} + e^{-K} K \to e^{-K} + e^{-K}\left(K|_{t<t_0} + R|_{t>t_0}\right)$$

correct only emission

- **Unitarized merging corrects Sudakov order by order to restore the cancellation**



$$e^{-K} + e^{-K} K \xrightarrow{\text{rewrite Sudakov}} 1 - e^{-K} K + e^{-K} K$$

$$\boxed{e^{-K} K \to e^{-K}\left(K|_{t<t_0} + R|_{t>t_0}\right)}$$

apply to both

UNLOPS

Hoeche, Lonnblad, Prestel, YL

- **Obtain NLO inclusive rate by adding additional terms**

"$>$" refers to $t > t_0$

"$<$" refers to $t < t_0$

$$e^{-K} + e^{-K} K \to 1 - e^{-K}(K_< + R_>) + e^{-K}(K_< + R_>)$$

$$\xrightarrow{\text{add NLO}} 1 + V + R - e^{-K}(K_< + R_>) + e^{-K}(K_< + R_>)$$

- **take merging scale to be as small as PS terminating scale**

$$t_0 \to t_c \sim 0 \Rightarrow \text{drop } K_<$$

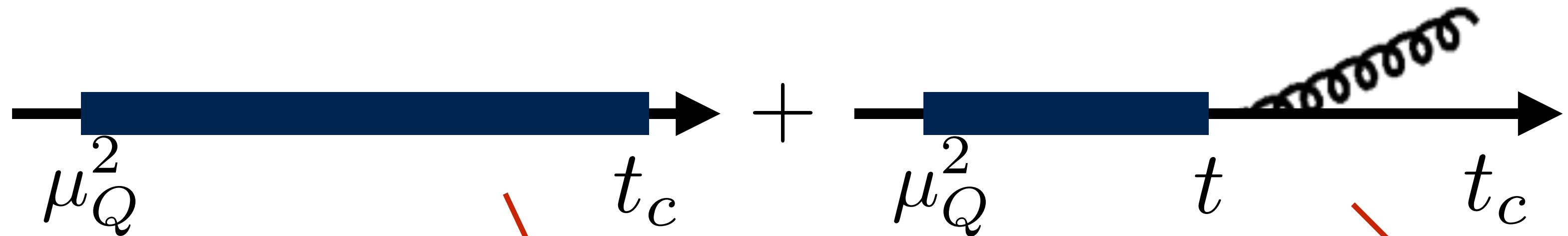
- **separate Real by the terminating/merging scale**

$$R = R_< + R_>$$

Phase Space Slicing

$$\boxed{e^{-K} + e^{-K} K \to 1 + V + R_< + (1 - e^{-K})R_> + e^{-K} R_>}$$

UNLOPS



$$e^{-K} + e^{-K}K \to 1 + V + R_< + (1-e^{-K})R_> + e^{-K}R_>$$

zero jet bin

one jet bin

- Correct emission pattern in hard region ✕ $e^{-K}R_> \to R$
- Keep PS resummation in IR region ✕ $e^{-K}R_> \to e^{-K}K$
- Correct NLO inclusive rate ✕ $\equiv 1 + V + R$

$(1-e^{-K})R_>$ obtained by probability conservation from $e^{-K}R_>$

- **Subsequent PS continues in the one jet bin**
- **Close related to the phase space slicing method**

UNLOPS vs. MC@NLO/POWHEG

$$\mathrm{MC@NLO/POWHEG}: (1+V+K)(e^{-K}+e^{-K}K)+(R-K)$$

$$\mathrm{UNLOPS}: 1+V+R_{<}+(1-e^{-K})R_{>}+e^{-K}R_{>}$$

- **Matching (MC@NLO/POWHEG)**
  - ***multiplicative*** *(V is showered)*
  - ***closely related to the subtraction method***

$$1+V+R=(1+V+K)+(R-K)$$

- **Merging (UNLOPS)**
  - ***additive*** *(V is not showered)*
  - ***closely related to the phase space slicing method***

$$1+V+R=(1+V+R_{<})+R_{>}$$

higher order effect ⇒ regarded as theoretical uncertainty

Extension to NNLO?

$$\mathrm{MC@NLO/POWHEG}: (1+V+K)(e^{-K}+e^{-K}K)+(R-K)$$

- **No generic extension**
  - **Currently no flexible subtraction method of NNLO**

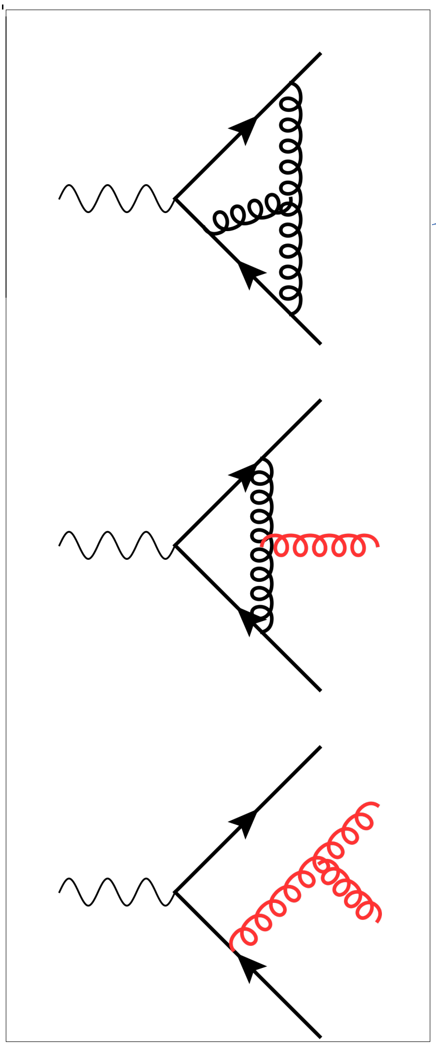
$$\mathrm{UNLOPS}: 1+V+R_{<}+(1-e^{-K})R_{>}+e^{-K}R_{>}$$

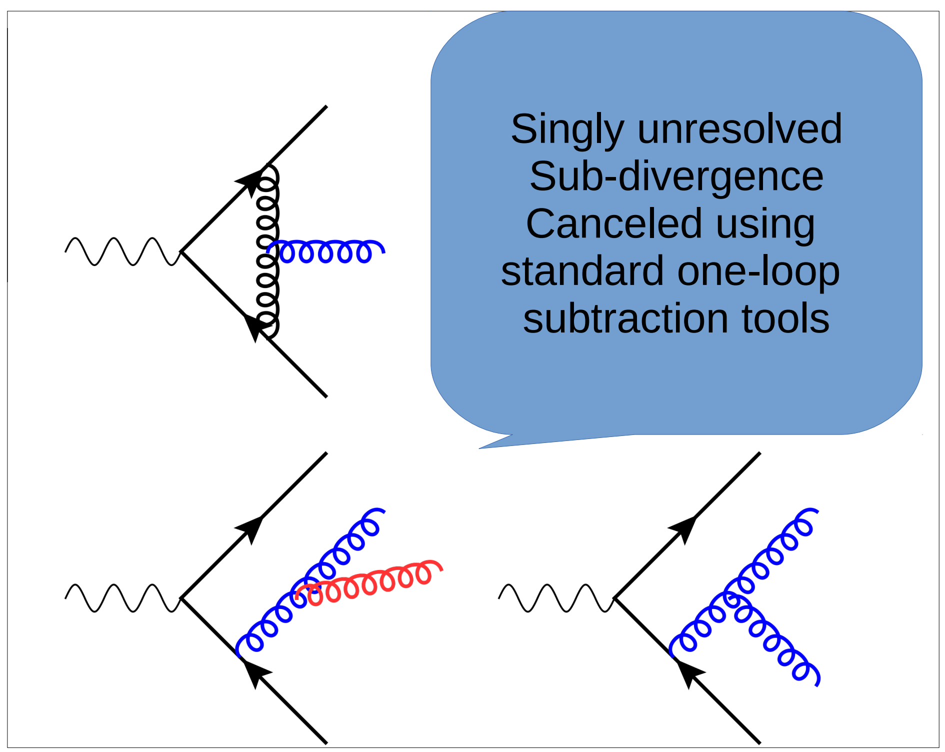
- **Straightforward generic extension**
  - **first need NNLO calculation with phase space slicing**

Sherpa NNLO

Catani, Grazzini

Approximate matrix element employed In doubly unresolved region. Integrate analytically





Doubly unresolved

Singly unresolved

Fully resolved

qT < qT cut-off
jet-vetoed NNLO

contains 2-loop virtual and IR limit of double real emission

qT > qT cut-off
H/W/Z + 1jet @ NLO

- **Phase space sliding method by H/W/Z qT** (based on qT subtraction by Catani and Grazzini)
  - **Above the cut-off: H/W/Z + 1jet @ NLO**
  - **Below the cut-off: Jet-vetoed NNLO**
    - **Well approximated by prediction from factorization theorem**

small qT cut-off ⇒
large cancellation ⇒
possible numerical instability

Sherpa NNLO

- full event generation
- interface with Rivet

...

- Sherpa now has H/W/Z production at NNLO
  - (Relatively) Easy to do
    - Sherpa already has W/Z/H+1jet at NLO from Blackhat and internal implementation - very stable

      Berger, Bern, Dixon, etc. Ravindran, Smith, van Neerven
    - Below qT cut-off obtained from existing SCET results - well established
  - Also combined with PS
    - Use the method of UN2LOPS

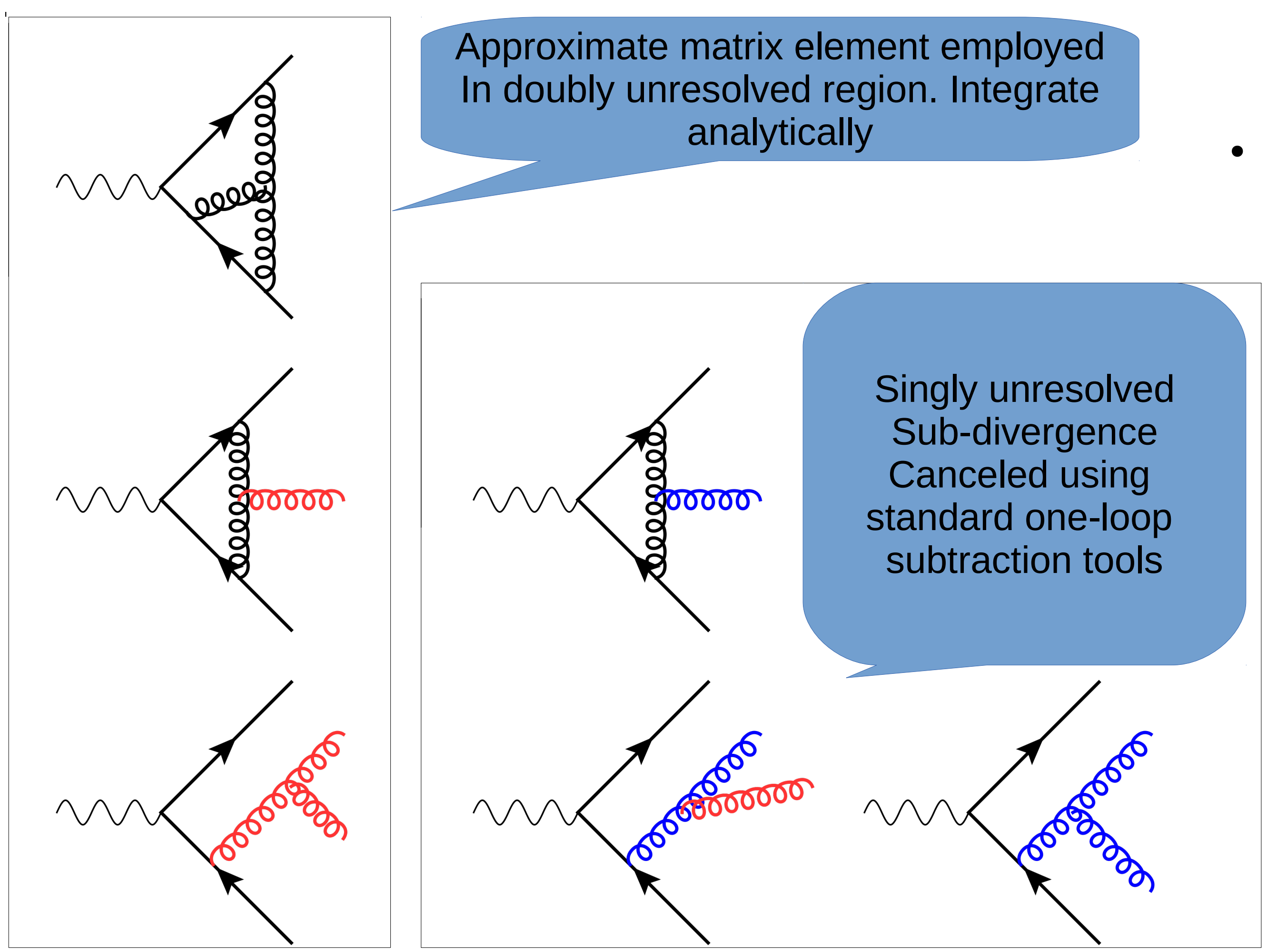
UNLOPS to UN2LOPS

$$\text{UNLOPS}: 1 + V + R_{<} + (1 - e^{-K}) R_{>} + e^{-K} R_{>}$$

qT < qT cut-off
Jet-vetoed NNLO
Born kinematics

qT > qT cut-off
NLO H/W/Z + 1jet
handled by MC@NLO

Residual IR divergence suppressed - incomplete
PS is only approx. NLL
NNLO contains NNLL



Doubly unresolved | Singly unresolved | Fully resolved

- **UN2LOPS**
  - **H/W/Z: NNLO inclu. accurate**
  - **H/W/Z + 1 jet: NLO inclu. accurate**
  - **H/W/Z + 2 jets: LO accurate**
  - **H/W/Z + >2 jets: PS accurate**
  - **H/W/Z + soft jets: most logs resummed (limited by PS accuracy)**

Final Formula

$$
\begin{aligned}
\langle O \rangle = & \int \mathrm{d}\Phi_0 \, \bar{\bar{\mathrm{B}}}_0^{t_c} \, O(\Phi_0) \\
& + \int_{t_c} \mathrm{d}\Phi_1 \left[1 - \Pi_0(t_1, \mu_Q^2) \left(w_1 + w_1^{(1)} + \Pi_0^{(1)}(t_1, \mu_Q^2) \right) \right] \mathrm{B}_1 \, O(\Phi_0) \\
& + \int_{t_c} \mathrm{d}\Phi_1 \, \Pi_0(t_1, \mu_Q^2) \left(w_1 + w_1^{(1)} + \Pi_0^{(1)}(t_1, \mu_Q^2) \right) \mathrm{B}_1 \, \bar{\mathcal{F}}_1(t_1, O) \\
& + \int_{t_c} \mathrm{d}\Phi_1 \left[1 - \Pi_0(t_1, \mu_Q^2)\right] \tilde{\mathrm{B}}_1^{\mathrm{R}} \, O(\Phi_0) + \int_{t_c} \mathrm{d}\Phi_1 \Pi_0(t_1, \mu_Q^2) \, \tilde{\mathrm{B}}_1^{\mathrm{R}} \, \bar{\mathcal{F}}_1(t_1, O) \\
& + \int_{t_c} \mathrm{d}\Phi_2 \left[1 - \Pi_0(t_1, \mu_Q^2)\right] \mathrm{H}_1^{\mathrm{R}} \, O(\Phi_0) + \int_{t_c} \mathrm{d}\Phi_2 \, \Pi_0(t_1, \mu_Q^2) \, \mathrm{H}_1^{\mathrm{R}} \, \mathcal{F}_2(t_2, O) \\
& + \int_{t_c} \mathrm{d}\Phi_2 \, \mathrm{H}_1^{\mathrm{E}} \, \mathcal{F}_2(t_2, O)
\end{aligned}
$$

- **Tree level amplitude and subtraction from Amegic or Comix**

  [Krauss,Kuhn,Soff] hep-ph/0109036, [Gleisberg,Krauss] arXiv:0709.2881, [Gleisberg,Hoeche] arXiv:0808.3674

- **One loop virtual matrix element from Blackhat, or internal Sherpa**

  [Berger et al.] arXiv:0803.4180, [Berger et al.] arXiv:0907.1984 arXiv:1004.1659 arXiv:1009.2338

- **NNLO vetoed cross section using recent SCET results**

  [Becher,Neubert] arXiv:1007.4005 arXiv:1212.2621, [Gehrmann,Luebbert,Yang] arXiv:1209.0682 arXiv:1403.6451 arXiv:1401.1222

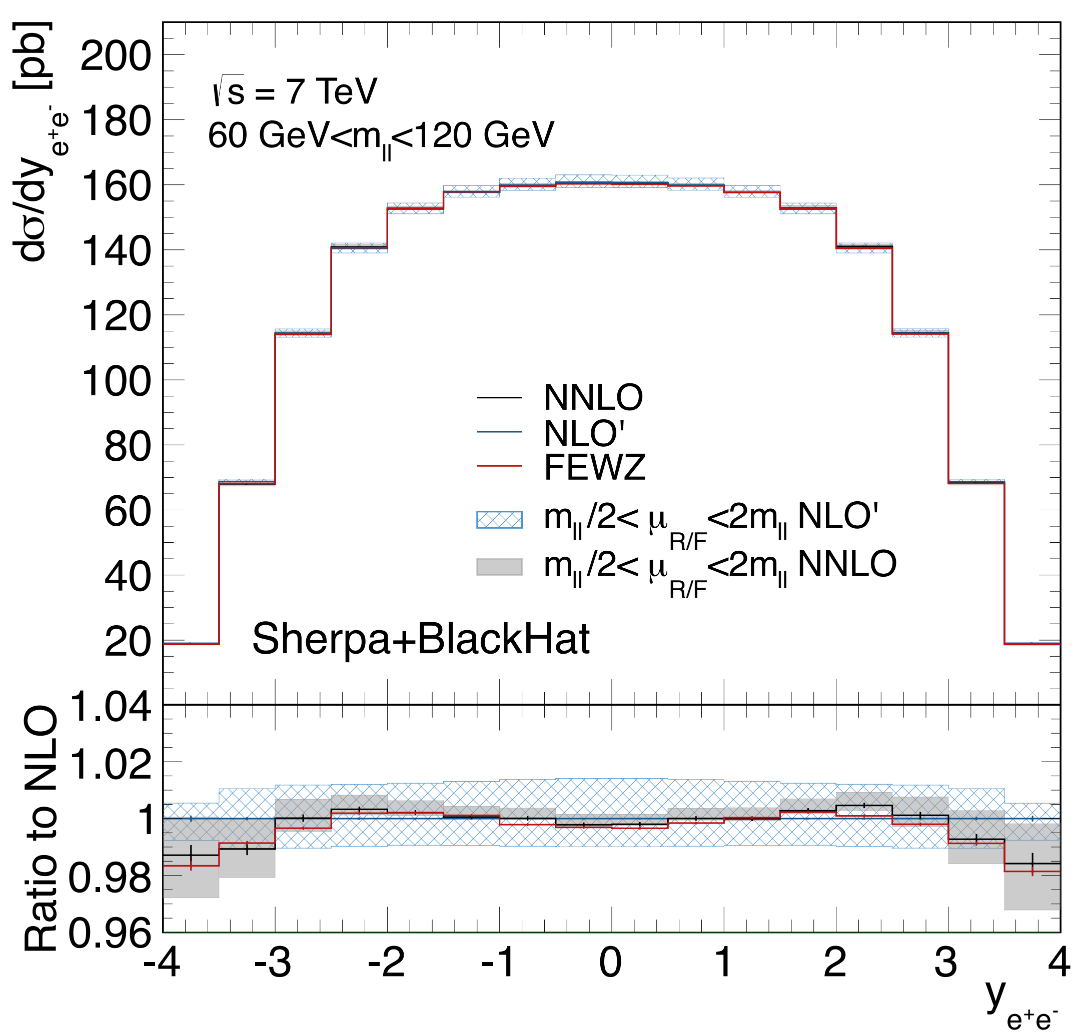
- **Parton shower based on Catani-Seymour dipole**

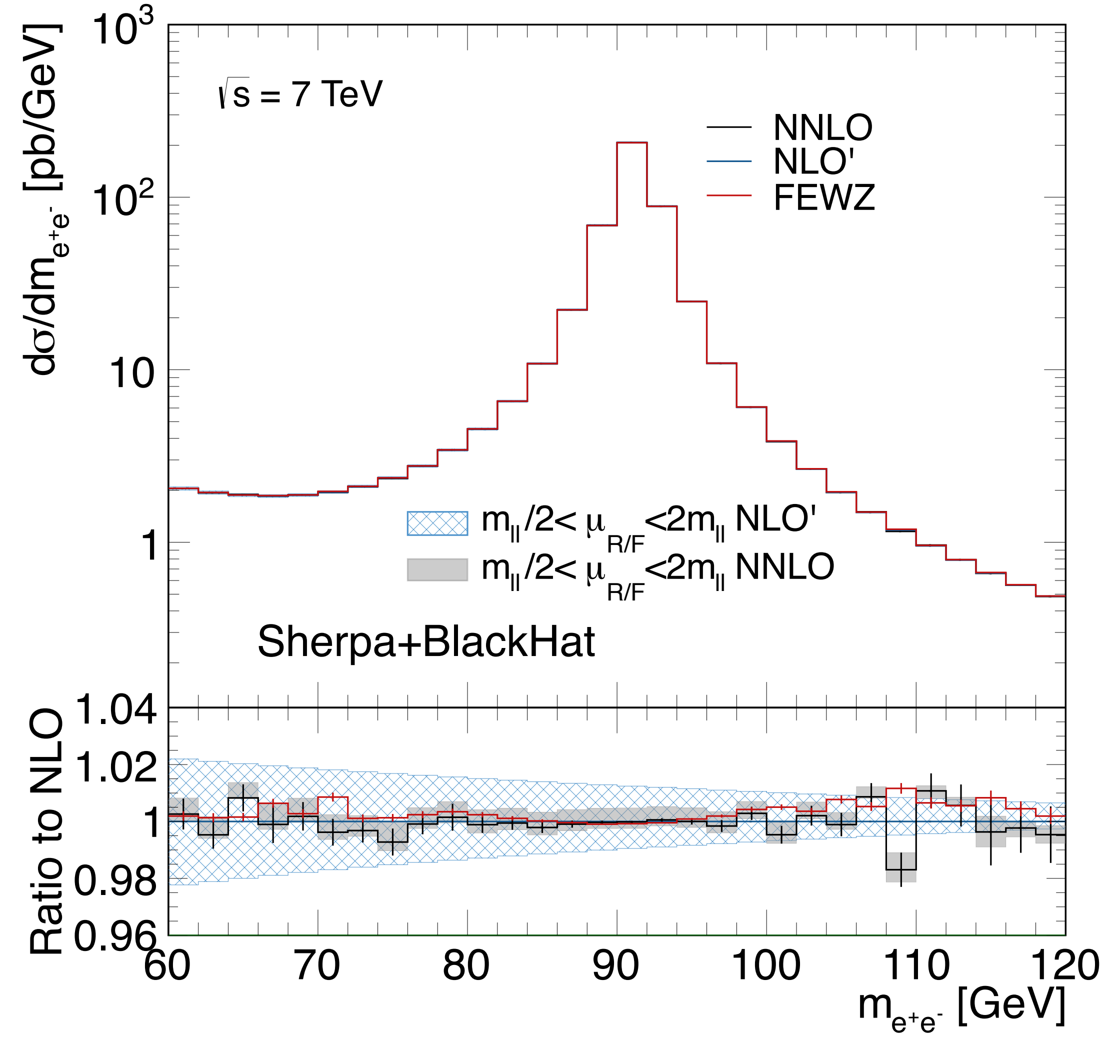
  [Schumann,Krauss] arXiv:0709.1027

- **Combined in Sherpa event generation framework**

  [Gleisberg et al.] hep-ph/0311263 arXiv:0811.4622

DY: Validation with FEWZ and VRAP

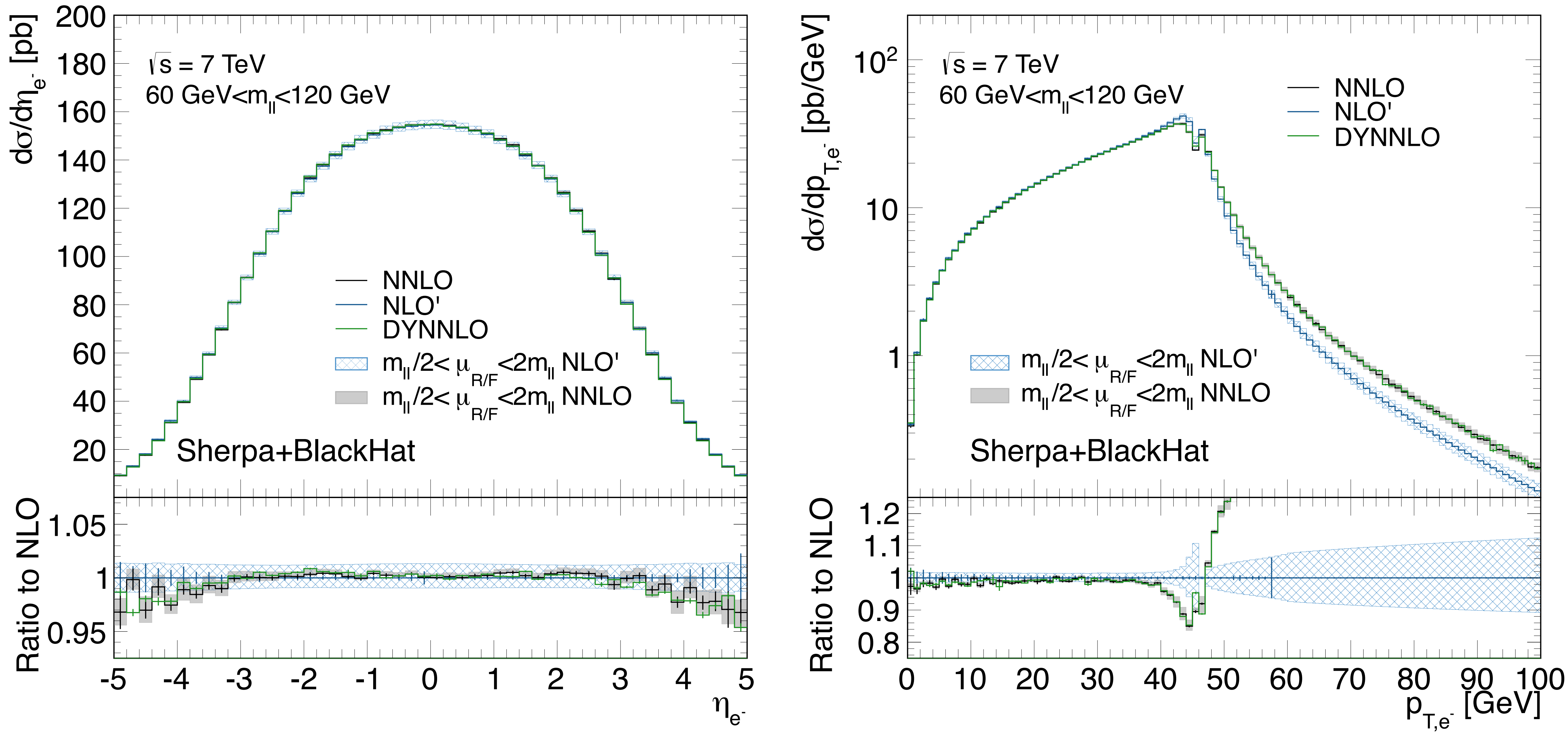




E_{cms}	7 TeV	14 TeV	33 TeV	100 TeV
VRAP	$973.99(9)^{+4.70}_{-1.84}$ pb	$2079.0(3)^{+14.7}_{-6.9}$ pb	$4909.7(8)^{+45.1}_{-27.2}$ pb	$13346(3)^{+129}_{-111}$ pb
SHERPA	$973.7(3)^{+4.78}_{-2.21}$ pb	$2078.2(10)^{+15.0}_{-8.0}$ pb	$4905.9(28)^{+45.1}_{-27.9}$ pb	$13340(14)^{+152}_{-110}$ pb

Hoeche, YL, Prestel arXiv:1405.3607

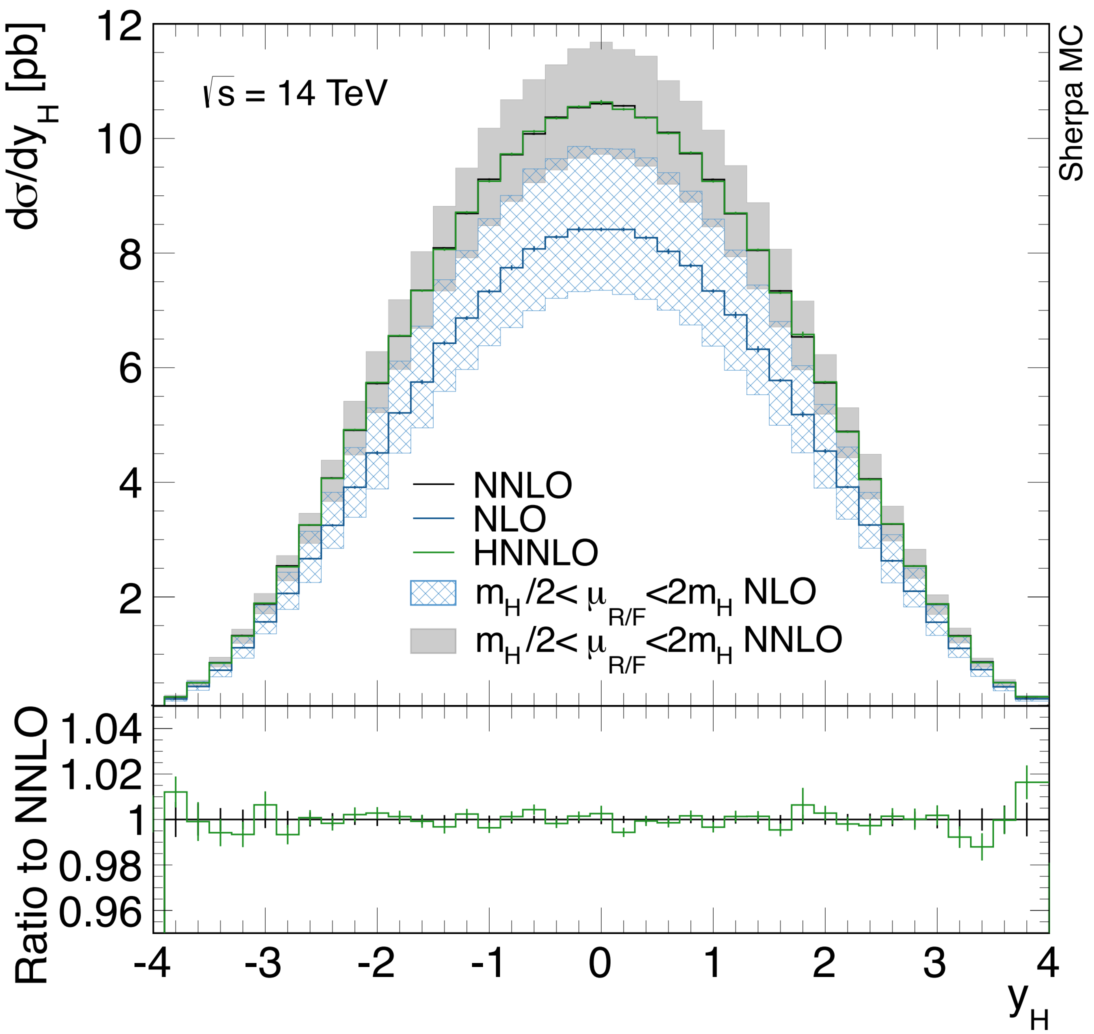
DY: Validation with DYNNLO

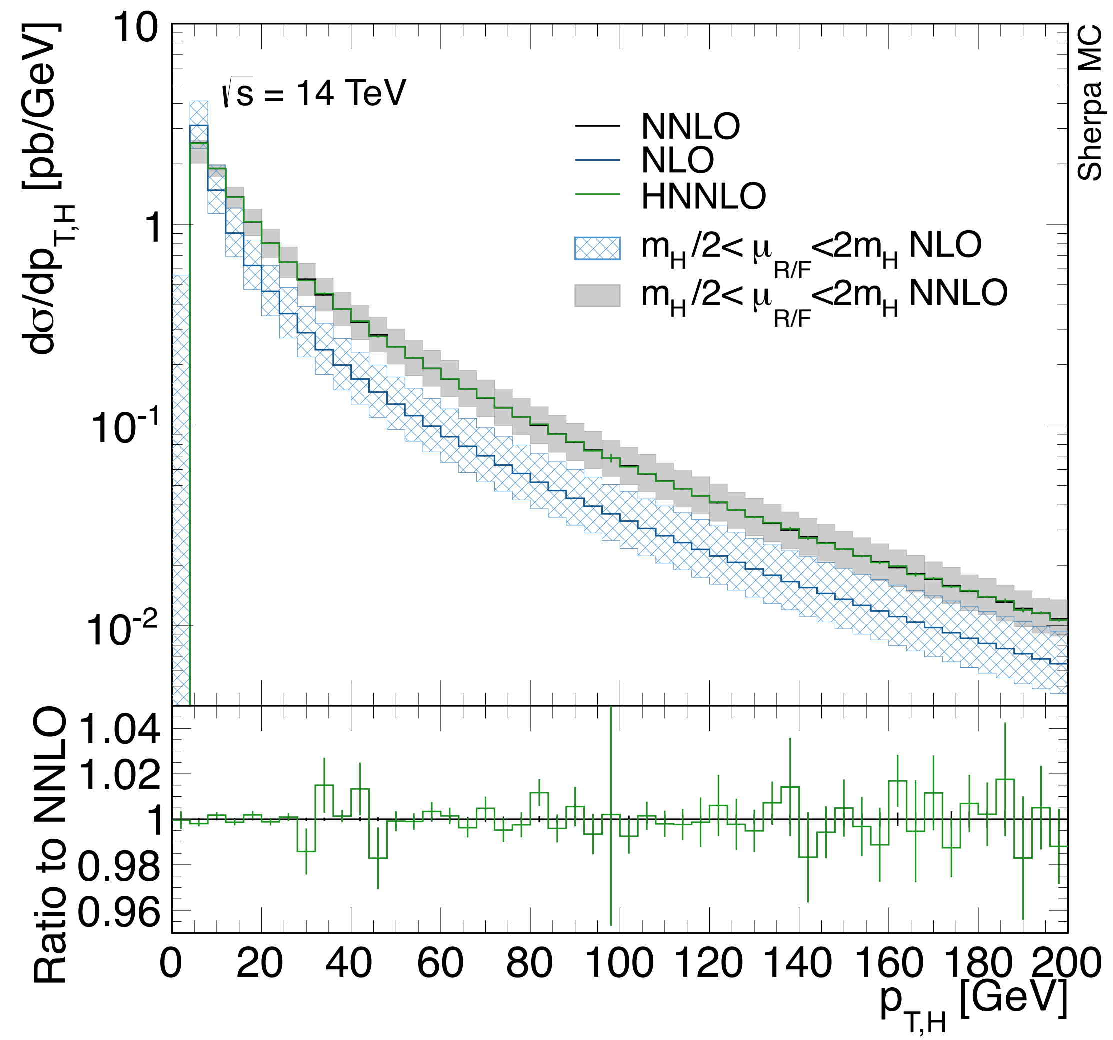


Hoeche, YL, Prestel arXiv:1405.3607

Higgs: Validation with HNNLO

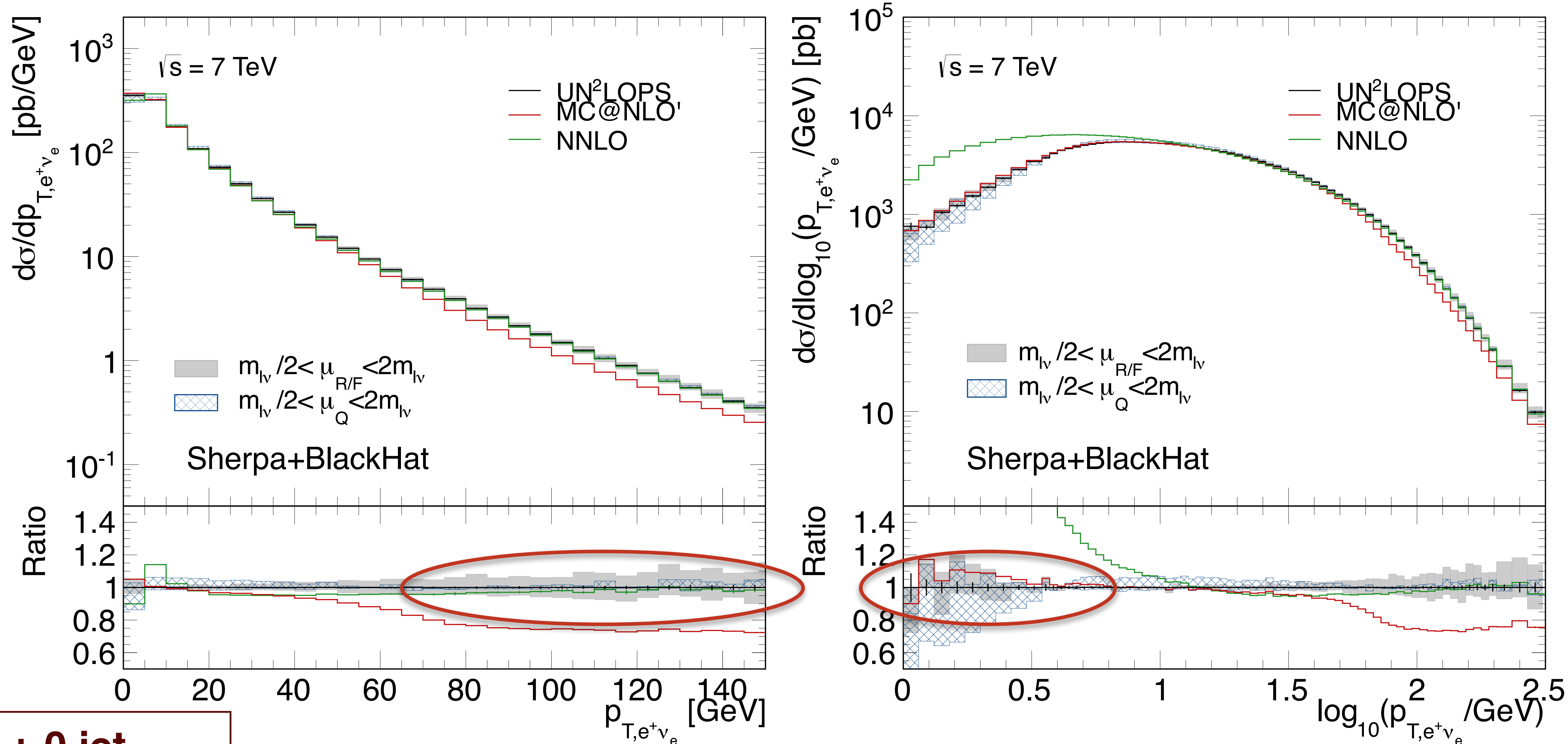
Hoeche, YL, Prestel, arXiv:1407.3773





E_{cms}	7 TeV	14 TeV	33 TeV	100 TeV
HNNLO	$13.494(7)^{+1.436}_{-1.382}$ pb	$44.550(16)^{+4.293}_{-3.954}$ pb	$160.84(13)^{+13.29}_{-12.36}$ pb	–
SHERPA	$13.515(7)^{+1.443}_{-1.382}$ pb	$44.559(36)^{+4.226}_{-3.929}$ pb	$160.39(17)^{+13.47}_{-11.88}$ pb	$670.1(10)^{+47.9}_{-39.4}$ pb

Hoeche, YL, Prestel arXiv:1405.3607

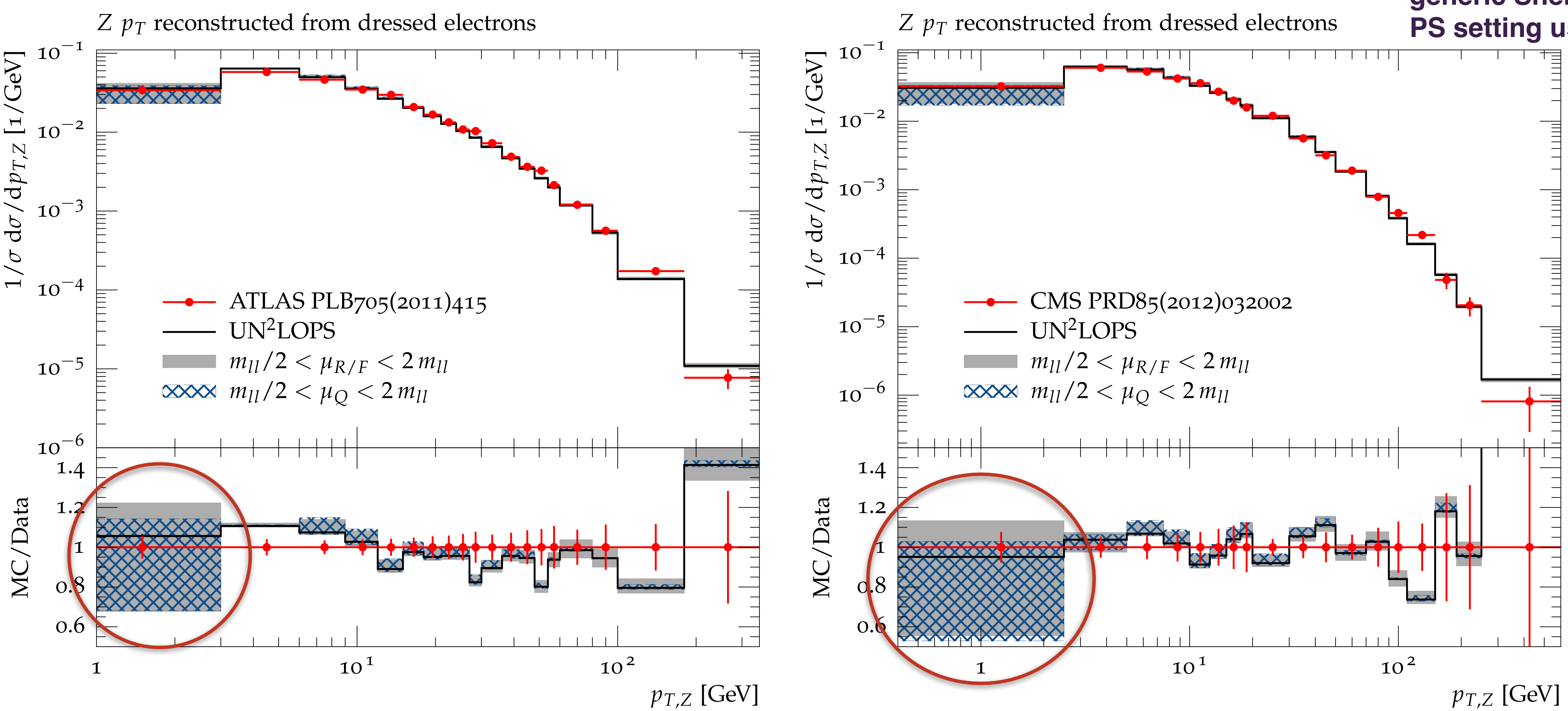


W + 0 jet
MC@NLO vs.
UN2LOPS

UN2LOPS at Work

- UN2LOPS trumps both MC@NLO for H/W/Z + 0 and 1 jet
  - Good agreement with W+0jet at low pT, and becomes W+1jet at high pT
  - Also correct inclusive NNLO rate W+0jet

Comparison with Exp.

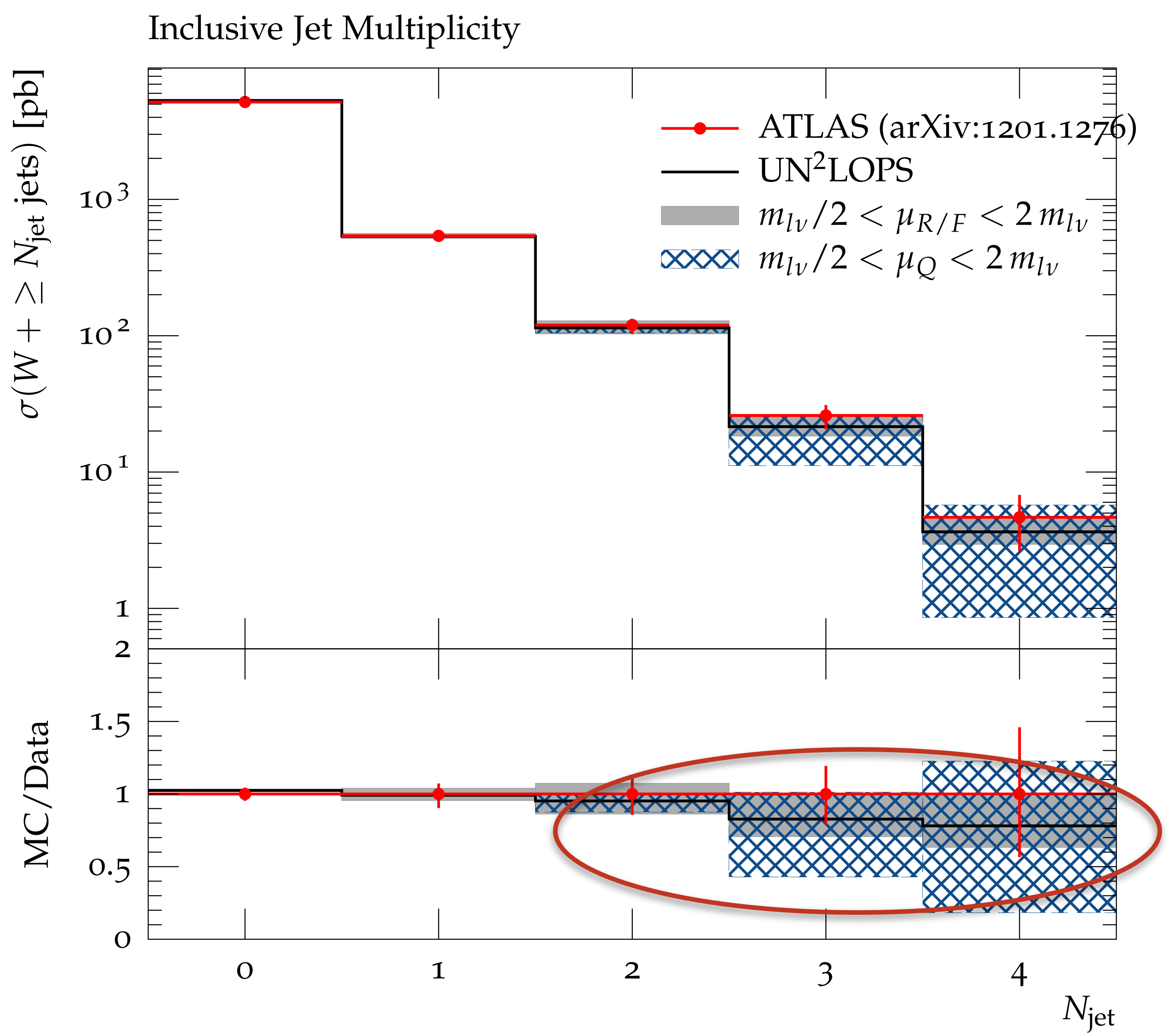


generic Sherpa PS setting used

pT axis in log scale

- **Largely agrees but large uncertainty in zero pT bin**
  - **Due to unresummed subleading logs of NNLO calculation**
  - **Scale variations of all finite pT bins propagate to zero pT bin by PS unitarity**

Comparison with Exp.



- **UN2LOPS acts on 0, 1 and 2 jet bin:**
  - **Excellent agreement**
  - **Reduced uncertainty**
- **Improvement by merging with W + 2,3,4 jets @ NLO**
  - **Further reduced uncertainty**

UN2LOPS with Higgs

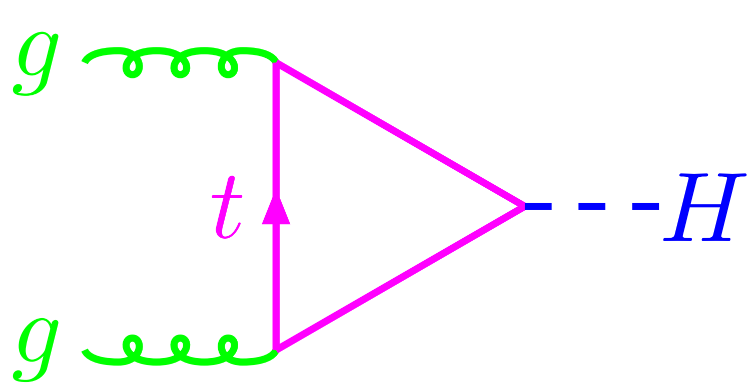
- **The Application to Higgs: slight complication involved**
  - **Higgs NNLO is only worked out in EFT framework in massive top limit**

$$\text{“SM Higgs NNLO”} \;= H_g \times \;\text{“EFT Higgs NNLO”}$$

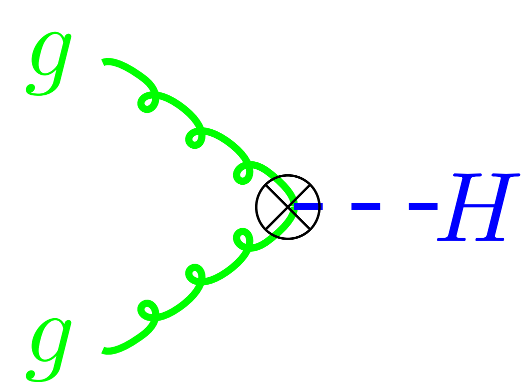
generic NNLO

  - **Square of H-g-g effective coupling**

$$H_g = |c_g|^2 = h^{(0)} + \frac{\alpha_S}{4\pi} h^{(1)} + \left(\frac{\alpha_S}{4\pi}\right)^2 h^{(2)} + \ldots$$



$\Rightarrow$



UN2LOPS with Higgs

- **In FO, product is expanded and truncated in α_s ⇒ "individual" matching**

$h^{(0)}$ is multiplied by generic Higgs NNLO matched with U2LOPS
$h^{(1)}$ is multiplied by generic Higgs NLO matched with MC@NLO
$h^{(2)}$ is multiplied by generic Higgs LO with simple parton shower

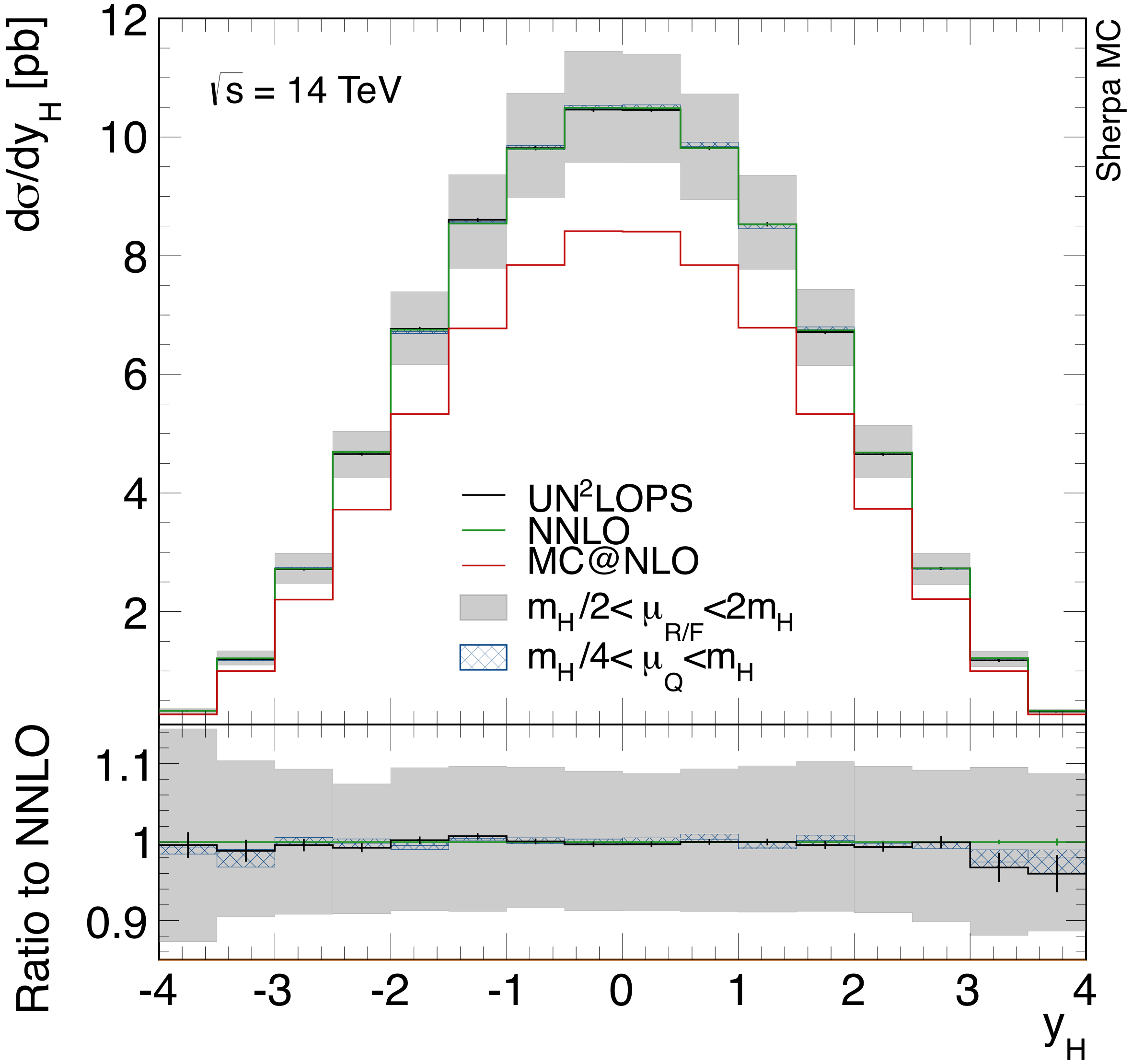
- **PS is all about factorization ⇒ "factorized" matching**

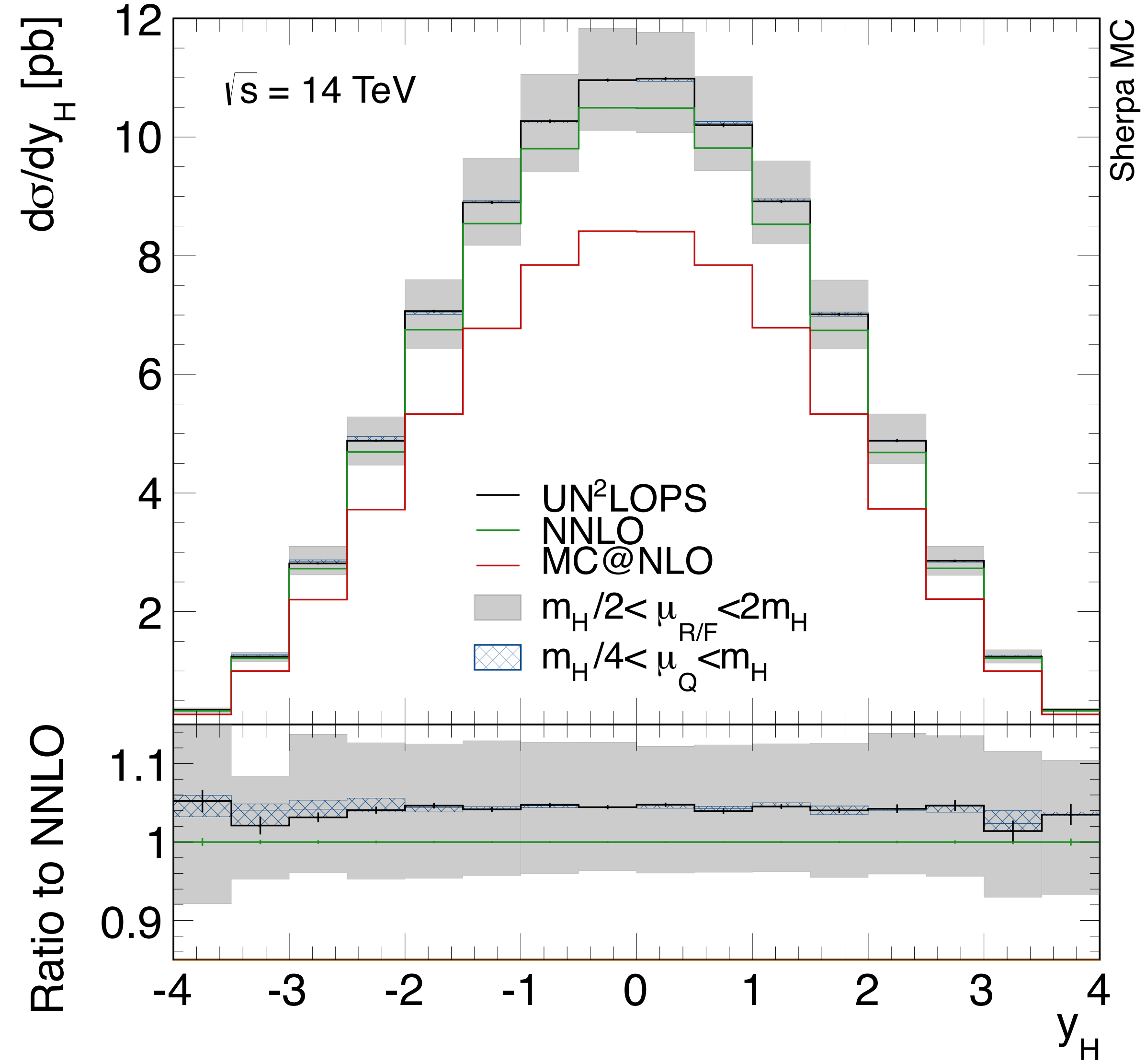
full H_g is multiplied by generic Higgs NNLO matched with U2LOPS

At 14TeV LHC, compared to "individual", "factorized" matching adds
14% w.r.t. Higgs LO
5% w.r.t. Higgs NNLO
because large Higgs NLO is further enhanced by HO terms of H_g

Higgs Rapidity

Hoeche, YL, Prestel arXiv:1407.3773





- left: “individual” matching; right: “factorized” matching
- Big improvement over MC@NLO
- Higgs rapidity spectrum unaffected by PS

Outlook

- **Provides experimental analysis with best theoretical accuracy at event out level**
  - **Straightforward to include finite top mass effect in UN2LOPS for Higgs**
  - **Same is true to include EW effects for both Higgs and DY processes**
- **UN2LOPS is a general framework**
  - **All differential NNLO calculation can be interfaced with** given a suitable cut-off/merging parameter
  - **Further improvement relies on an improved parton shower**

Outlook

- **For well studied processes like Higgs and DY, an improved parton shower could be implemented based on analytic resummation**
  essentially adding ad-hoc terms to the parton shower kernels in order to reproduce the Sudakov form factor accurate to NNLL
  work in progress
  - **Pros**
    All NNLO divergences are within control
    Uncertainty of parton shower is reduced
  - **Cons**
    Sudakov from analytic resummation is process-specific and observable-dependent

Summary

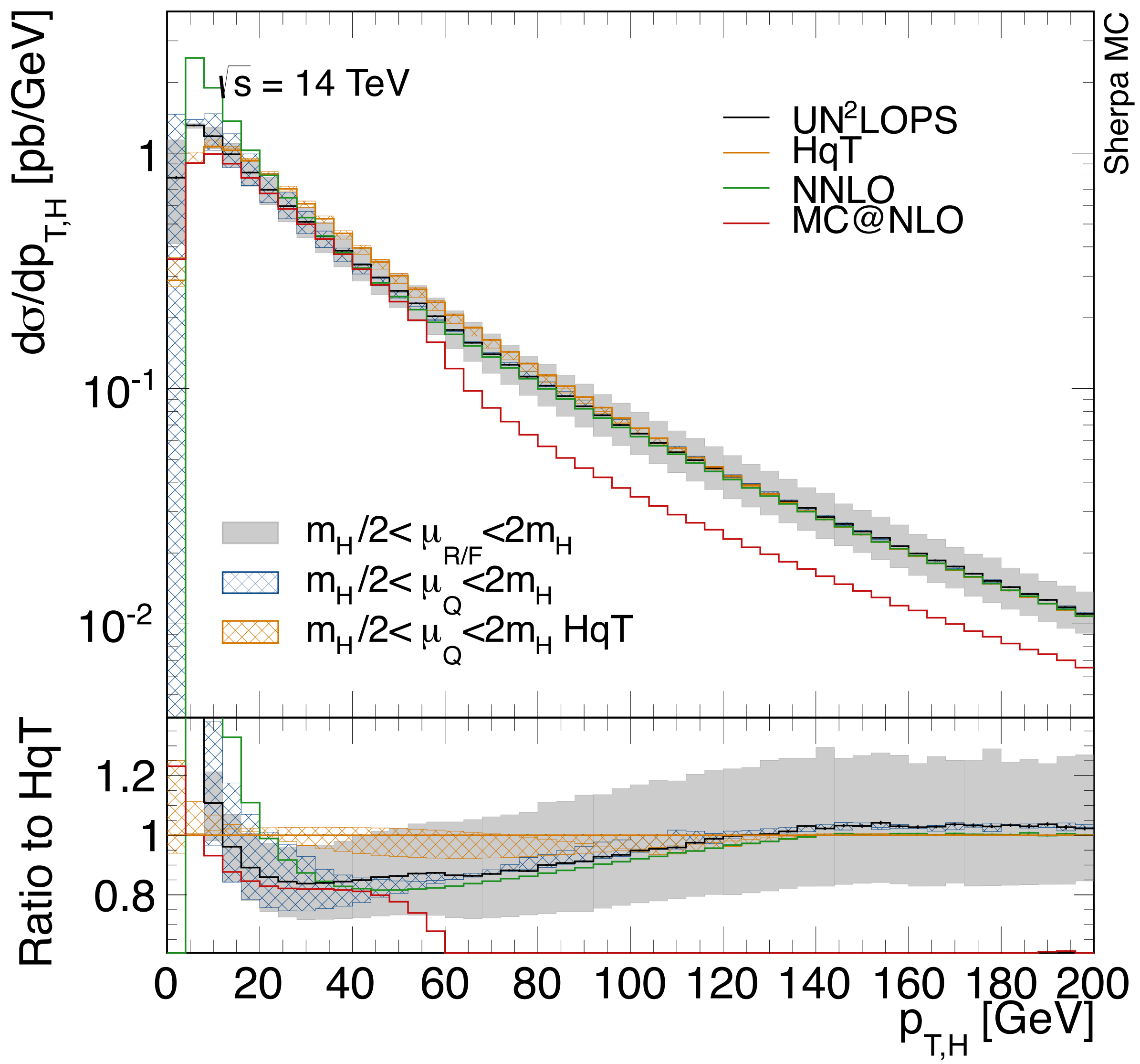
- **First practical implementation of NNLO+PS for DY processes, also applied to Higgs production**
  - **Truly accessible NNLO for experimental analysis**
  - **Improved precision for Higgs and BSM study**
  - **Reduced uncertainty in traditional PS**
- **Flexible implementation, thanks to the Sherpa framework**
  - **Event generation at both NNLO and NNLO+PS**
  - **Interface with analysis tools such as Rivet available**
  - **Plugin to Sherpa (provided upon request)**
- **Parton shower improvement desirable for better overall accuracy**

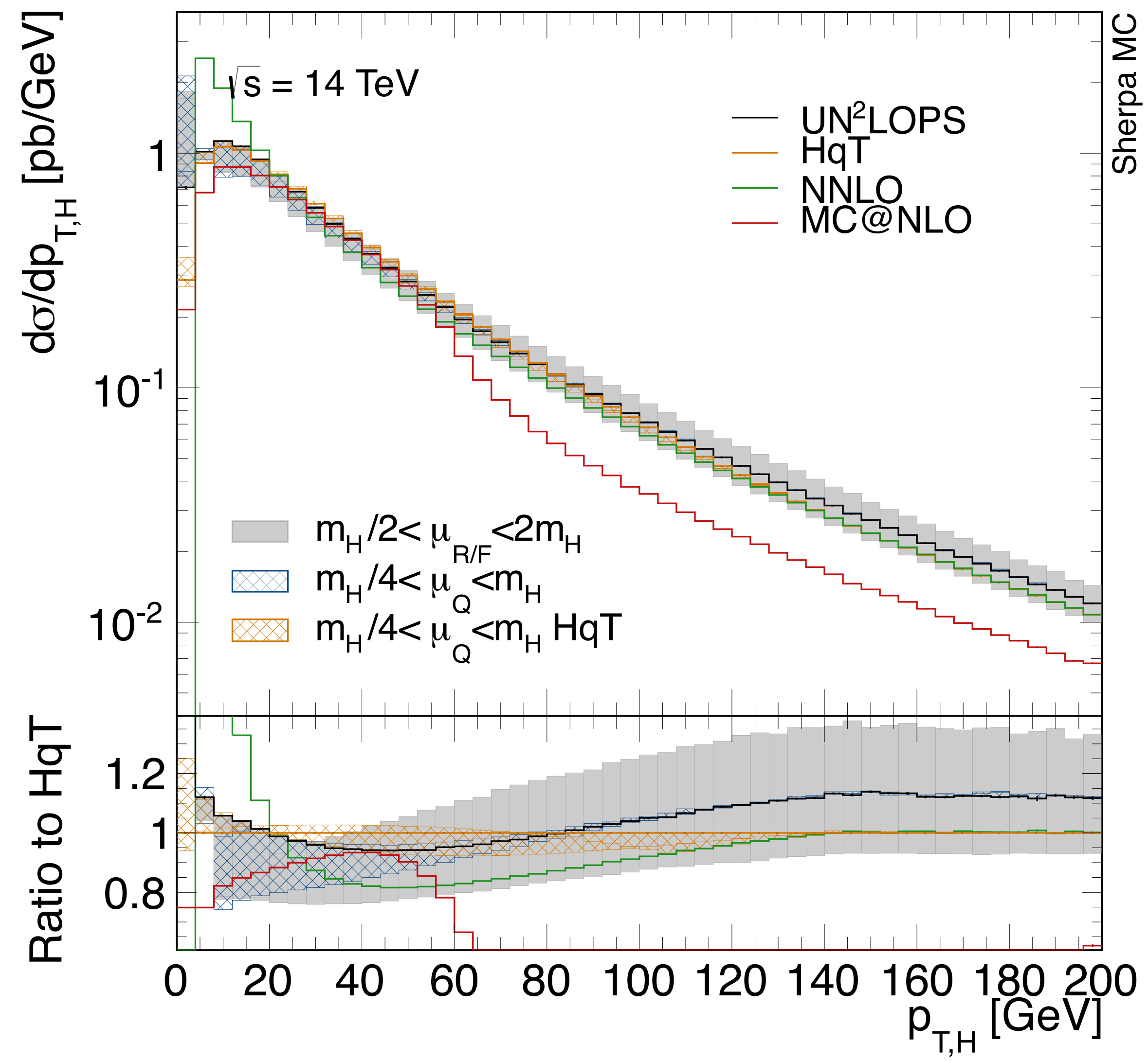
Back Up

Higgs pT distribution

HqT: state-of-the-art NNLO+NNLL Bozzi, Catani, De Florian, Ferrera, Grazzini, Tommasini

Hoeche, YL, Prestel arXiv:1407.3773





- **Harder pT spectrum in “factorized” matching**
- **Lower resummation accuracy of UN2LOPS than HqT**